Shaking Table Model of a Concrete Gravity Dam for Computer Code Validation
Monolithic Model

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Safety of dams under earthquake loading has always been a major concern in seismically active regions because of the high potential hazard that uncontrolled release of the reservoir poses to the population downstream of the dam. The current practice for the evaluation of the dynamic response of concrete dams at the U.S. Bureau of Reclamation is to initially preform a linear elastic finite element analysis of the structure under static loads plus the maximum credible earthquake predicted to occur at the site. If the response of the structure indicates that significant cracking damage would occur based on high tensile stress results, then non-linear analyses would be completed.In recent years a number of finite element programs have become available to structural engineers which provide the capability of modeling vertical contraction joint opening and concrete cracking which may occur in concrete arch dams during a seismic event. The Bureau of Reclamation has recently purchased the ABAQUS finite element program which is capable of performing non-linear cracking analyses. The ABAQUS program includes a brittle cracking material model for concrete. This is a fairly complex analytical tool and engineers in Reclamation's structural analysis group need to develop expertise in performing and understanding non-linear modeling and analysis techniques. A set of calibration models would provide a valuable data set for those performing the numerical studies to assure that known results can be obtained. Structural engineers and material engineers need to work closely to develop new standards for material testing so that the appropriate material properties are available for these analyses. Therefore a shaking table test of a 1/50 scale cantilever monolith of Koyna Dam was built at Reclamation's Material Testing Laboratory for use in calibrating linear-elastic and non-linear material properties, as well as to provide a means of evaluating the effect of various analysis parameters available in the ABAQUS program. Two models were tested, a model with a natural but preexisting crack and a monolithic model.

The ultimate goal of the shaking table test program was to develop a correlation between the material testing program and material property requirements for the non-linear numerical concrete cracking model. But before this goal can be accomplished the basic linear elastic material properties needed to be calibrated and the effects of various analysis parameters needed to be understood. These requirements were accomplished through comparisons of analytical results with laboratory measurements. This report is concerned primarily with these preliminary studies, although some non-linear analysis results are also presented

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I INTRODUCTION

Safety of dams under earthquake loading has always been a major concern in seismically active regions because of the high potential hazard that uncontrolled release of the reservoir poses to the population downstream of the dam. The current practice for the evaluation of the dynamic response of concrete dams at the U.S. Bureau of Reclamation is to initially preform a linear elastic finite element analysis of the structure under static loads plus the maximum credible earthquake predicted to occur at the site. If the response of the structure indicates that significant cracking damage would occur based on high tensile stress results, then non-linear analyses would be completed. In recent years a number of finite element programs have become available to structural engineers which provide the capability of modeling vertical contraction joint opening and concrete cracking which may occur in concrete arch dams during a seismic event. The Bureau of Reclamation has recently purchased the ABAQUS finite element program which is capable of performing non-linear cracking analyses. The ABAQUS program includes a brittle cracking material model for concrete. This is a fairly complex analytical tool and engineers in Reclamation's structural analysis group need to develop expertise in performing and understanding non-linear modeling and analysis techniques. A set of calibration models would provide a valuable data set for those performing the numerical studies to assure that known results can be obtained. Structural engineers and material engineers need to work closely to develop new standards for material testing so that the appropriate material properties are available for these analyses. Therefore a shaking table test of a 1/50 scale cantilever monolith of Koyna Dam was built at Reclamation's Material Testing Laboratory for use in calibrating linear-elastic and non-linear material properties, as well as to provide a means of evaluating the effect of various analysis parameters available in the ABAQUS program. Two models were tested, a model with a natural but preexisting crack and a monolithic model.

The ultimate goal of the shaking table test program was to develop a correlation between the material testing program and material property requirements for the non-linear numerical concrete cracking model. But before this goal can be accomplished the basic linear elastic material properties needed to be calibrated and the effects of various analysis parameters needed to be understood. These requirements were accomplished through comparisons of analytical results with laboratory measurements. This report is concerned primarily with these preliminary studies, although some non-linear analysis results are also presented.

II LOW STRENGTH MATERIAL DESIGN AND TESTING

II.1 Similitude Requirements

Koyna Dam is a 338 foot high concrete gravity dam in India which suffered cracking during a magnitude 6.5 earthquake in 1967. The geometry of the shake table model was scaled from Koyna Dam. Previous shake table research was completed by Doctors Akira Niwa and Ray Clough in 1980[7]. They performed shaking table tests to investigate the feasibility of studying the nonlinear response behavior of concrete dams. Their research concluded that shaking table research is a practical means of studying the nonlinear earthquake response of concrete dams and obtaining their actual failure mechanisms.

In the present study numerical models were compared to laboratory results so exact similitude relationships were not required but to the extent possible similitude relationships were maintained. The model scale chosen was 1/50 scale. Similitude requirements for the models, estimated dam material properties, associated scale factors and the model material target values are summarized in Tables 1 and 2.

Table 1: Similitude Requirements For a 1/50 Scale Dam Model		
Component	Variable	Required Scale Ratio model / prototype
Dam	Unit Weight Length Elastic Modulus Ultimate Strength Poisson's Ratio Strain Force	$\rho = 1$ $L = 1/50$ $E = 1/50$ $\sigma = 1/50$ $\nu = 1$ $\varepsilon = 1$ $F = (1/50)^3$
Earthquake Motion	Displacement Acceleration Duration and Period	$L = 1/50$ $a = 1$ $T = (1/50)^{1/2}$

Table 2 : Dam Material Properties			
Property	Prototype Estimate	Scale Factor	Target Value
E	4,000,000 psi	1/50	80,000 psi
f_c'	4,000 psi	1/50	80 psi
f_t	400 psi	1/50	8 psi
Density	150 pcf	1	150 psi
ε_u^c	0.0025	1	0.0025
ε_u^t	0.00012	1	0.00012

II.2 Concrete Mix Design

In this study a low strength concrete mix was designed to produce a concrete like material which would to the extent possible maintain similitude relationships, and yet be simple enough for direct comparisons with computer predicted results. Consideration was also given to reproducing the correct failure mechanism at model scale. A trial mix was initially made in the U.S. Bureau of Reclamation Materials Testing Laboratory. Bentonite pellets were used to reduce the material strength. In the laboratory trial mix the bentonite pellets were saturated overnight before they were added to the mix. Material property testing was completed on the trial mix which resulted in reasonable strength properties for use in the test model. Then a commercial concrete company(Colorado Ready Mix) was hired to produce the approximately 6 cubic yards of material needed for the model. The commercial company attempted to accomplish the saturation in the mixer drum during transit. The water was also adjusted from the original design at the plant due to the desire to decrease sloshing in transit. As a result the material properties of the commercially supplied material actually used in the model were not the same as those produced in the laboratory trial mix. Table 3 shows the mix components for both the laboratory trial mix and the commercially supplied mix which was actually used in the model. The material properties produced in the laboratory trial mix and the commercially produced mix are shown in Table 4.

Table 3 : Model Concrete Mix Components

Component	Lab Mix Wt. per cu. Yd.	Volume in mix	Model Mix Wt. per cu. Yd.	Volume in Mix
Air		0.14 (assumed by 1/2% entrapped air)		0.52
Water	560	8.99	480	7.68
Cement	160	0.82	168	0.86
Bentonite	40	0.25	42	0.26
Sand	1336	8.4	1454	8.87
No. 4 - 3.8" Gravel	553	3.36		

II.3 Laboratory Material Property Test Results

Both standard and specialized laboratory testing was done in the material testing laboratory[9]. Static compressive strength was determined following the American Society for Testing and Materials (ASTM) C 39 "Standard Test Method for Compressive Strength of Cylindrical Specimens." The modulus of elasticity was determined as per ASTM C 469 "Standard Test Method for Modulus of Elasticity and Poisson's Ratio in Compression."[1] All of the compressive cylinder tests failed in a classic shear plane typical of concrete (approximately 65 degrees). Figures A.1 through A.3 show the resulting stress-strain curves for three tests.

Dynamic tests were performed following the ASTM procedures for the static tests with the exception of loading rate. A uniaxial testing machine capable of providing failures within a strain rate of 10^{-3} and a time frame of approximately 0.1 seconds was used for the three dynamic compression tests. Figures A.4 through A.6 show the stress-strain curves resulting from the rapid compression tests. Typical unload-reload data resulting from cyclic compression tests is shown in Figures A.7 and A.8. Fracture (crack width versus load - beam test) data is shown in Figure A.9. The material density was measured as 138.2 pcf.

Table 4 : Laboratory Material Test Results
Material Properties for Koyna Dam (Monolithic Model) Low Strength Concrete
Age: 15 days

PROPERTY	ACTUAL KOYNA MIX	TARGET VALUE
Slump	8 inches	8 inches
Density	138.2 lb/ft^3	150 lb/ft^3
Static Modulus of Elasticity	157,000 lb/in^2	80,000 lb/in^2
Dynamic Modulus of Elasticity	113,000 lb/in^2	-
Ultimate Static Compressive Strength	203 lb/in^2	80 lb/in^2
Static Tension		
Splitting Tension	27 lb/in^2	8 lb/in^2
Beam Tension	60 lb/in^2	8 lb/in^2
Dynamic Tension	52 lb/in^2	-
Ultimate Strain (ε_u^c)	0.004	0.0025

III LABORATORY SHAKE TEST SET-UP AND PROCEDURE

III.1 Model Geometry

The laboratory shake table tests were completed at the U.S. Bureau of Reclamation, Materials Engineering and Research Laboratory[9]. A shake table for large scale tests has been in existence at Reclamation since 1969. The shake table was set up for this experiment using steel I beams to attach the Koyna scaled model to the table. Figure B.1 shows the Koyna monolithic model mounted on the shake table. Accelerations were applied to the model in the upstream downstream direction only(one dimensional shake test). The table was tested using ultrasonic methods for response modes and tested in motion with accelerometers to determine capabilities for higher frequencies. Input frequencies below 26 Hz gave good responses but higher frequencies were eliminated from testing. Response of the table was clearly best at frequencies of 26 Hz and below. A similitude simulation of an earthquake motion was not used. Rather, for practical reasons associated with the table, and for simplicity in numerical model calibration a sinusoidal motion was selected.

Figure B.2 and B.3 show the Koyna scaled model geometry and the steel I beam setup. The 1/50 scale model resulted in a 8.5 foot tall model weighing 7850 pounds. The first model tested was cast laying down on its side. The casting and forming operation was easier to completed in this case, but after a period of approximately 20 days a small shrinkage crack appeared in the exposed face. When at approximately 28 days, the model was positioned on the shake table and the forms were removed. The shrinkage crack was evident on all four faces of the model so it was assumed to extend through the model thickness. The plane of the crack had an inclination of approximately 20 degrees from horizontal towards the side of the model. This model is referred to in this report as the "cracked" model in reference to the preexisting shrinkage crack. The second model tested had the concrete forms constructed on the shake table so that the concrete for the model could be poured on the shake table with the model in the upright position. This was done to avoid the potential for shrinkage cracking. By pouring the second model upright on the shake table, and by testing earlier(15 days) the onset of shrinkage cracking was avoided and the second "monolithic" or "uncracked" model produced a material failure under dynamic loading. Earlier testing also held the curing strengths lower. The test cylinders of this material were poured on the same day as the model and tested immediately following the breaking of the model.

III.2 Loads

The only static load included in the analyses in this study was the gravity load. The primary focus of this study was the dynamic material properties and the response of the model to dynamic loading. Two input motions were used in the monolithic model study. The first input record (SHAKEA) was used to determine the natural frequencies of the model. The second input record (SHAKEB) was used to fail the model.

SHAKEA was a sinusoidal forcing motion applied to the model in the upstream/downstream direction only, with a constant acceleration of 0.1 g, and with frequencies starting at 2 Hz, and then increasing in 2 Hz increments to 30 Hz. The acceleration time history plot (Figure B.4) shows the upstream-downstream acceleration time history measured at the base of the model(Accel#1). This acceleration time history was used as an input motion for the ABAQUS analyses.

SHAKEB was a sinusoidal forcing motion with a constant frequency of 14 Hz(figure B.5). In this input record the acceleration amplitude was increased in 0.2 g increments until failure of the model occurred. This input motion was selected at the time of placement of the cracked model(Koyna I). Numerical analyses for the cracked model predicted a fundamental mode of 14 Hz. The results of the cracked model study are not included in this report, they are mentioned here only in reference to the selection of a 14 Hz sinusoidal input motion for the laboratory tests in which the models were shaken to failure.

The acceleration response spectra at 5 percent damping for both input motions are shown in Figure B.6. The response spectrum for input record SHAKEA indicates that structures with a natural frequency in the range of 3 to 5 Hz would have the most significant response to this input record. The response spectrum for input record SHAKEB indicates that structures with a natural frequency in the range of 14 to 15 Hz would have the most significant response, as expected. These response spectra were used as input for response spectrum analyses in ABAQUS.

III.3 Boundary Conditions

The rectangular base of the model was poured continuously with the Koyna portion of the model and acts as a foundation block. All-thread rods were embedded in the foundation to provide a means of anchoring the model to the shake table as shown in Figure B.1. Some unforseen problems with these boundary conditions developed during the test in which the model was shaken to failure. Prior to failure of the dam, the all-thread rods embedded in the base of the model began to break loose allowing the model to rock. As more material around the all-threads failed, the rocking of the model increased which resulted in increasing vertical accelerations. Eventually the material failure around the all-thread was severe enough that the entire model could slide back and forth a small amount in the direction of the excitation. This was evident in the measured displacement time history records shown in Figure B.7 at LVDT#1 which was located on the model base. The figure shows that the displacements oscillated about an initial offset of approximately -0.04 inches until approximately 300 seconds into the test. From this time on the position about which the measured displacements tended to oscillate drifted and an indeterminate non-linear boundary condition had developed. No attempt was made to duplicate these non-linear boundary conditions in the numerical analysis, but it is believed that general comparisons can still be made based on the final accelerations and the material properties presented.

III.4 Instrumentation

Instrumentation was designed to measure displacements, and accelerations on the model. The general instrumentation locations are shown in Figure B.8 Accelerometers #1, #4, #5, and #6 were positioned at various elevations on the upstream face of the Koyna model and set to measure horizontal accelerations in the upstream/downstream direction. Accelerometers #1, #2, and #3 are all located at the same position and measure accelerations in the upstream/downstream, cross-canyon, and vertical directions respectively. These three instruments were positioned at the top of the foundation block on the upstream face of the model. Accelerometer #8 was positioned at the center of the top surface of the model and was set to measure vertical accelerations. Four LVDT's were used to measure upstream/downstream displacement time histories during the laboratory tests. LVDT#1 was positioned on the downstream face of the foundation block. LVDT#2 was positioned on the upstream face at a height of approximately 5 foot above the bottom of the foundation block. LVDT#3 was positioned on the sloping surface of the downstream face, while LVDT#4 was positioned above the change in slope on the downstream face. All of the instruments were placed at the model center line with respect to the cross canyon direction.

IV LABORATORY SHAKE TEST RESULTS

IV.1 Modal Characteristics Determined From Laboratory Measurements

The acceleration time histories recorded during the laboratory test using input record SHAKEA provide an indication of the modal characteristics of the model. Since the frequency of the input motion in SHAKEA was stepped through even frequencies from 2 to 30 Hz at a constant amplitude, any clear jumps seen in the accelerations measured on the model can be used to identify resonant frequencies in the model. Figures C.1 and C.2 show the acceleration time histories measured at each of eight accelerometers during the laboratory test using input motion SHAKEA. Figure C.1 shows the upstream-downstream, cross-canyon, and vertical acceleration time histories measured at the base of the model using accelerometers #1, #2, and #3.. Figure C.2 shows the vertical acceleration time history measured at the top of the model using accelerometer #8. Figure C.1 and figure C.2 show the upstream-downstream acceleration time histories measured at accelerometers #4, #5, #6 and #7.

These acceleration records also provide evidence concerning the orientation of the mode shapes associated with these resonant frequencies. The plots show that a significant jump in the model's cross-canyon and vertical response occurred at an input frequency of 18 Hz. A corresponding jump is not seen in the upstream-downstream records. Measurements from accelerometers #5, #6, and #7 actually show a decrease in upstream-downstream response when the input motion's frequency was 18 Hz. This suggests that the models first mode acts primarily in the cross-canyon and vertical directions and that the first natural frequency is approximately 18 Hz. The upstream-downstream accelerations also show a gradual increase in amplitude peaking at 24 Hz suggesting that a second cantilever mode acting in the upstream-downstream direction <u>may</u> occur at 24 Hz.

There was also a definite jump in the model's cross-canyon response to the input motion at a frequency of 30 Hz. The model's upstream-downstream and vertical responses were also high at 30 Hz. This is the first resonant frequency of the table and may not be significant in terms of the response of the model.

Since the material properties of the model effect the mode shapes and natural frequencies, it may be possible to use this information from the excitation of the laboratory model in conjunction with the material property testing to calibrate the material properties used in the finite element model. Therefore numerous frequency analyses were completed for the uncracked Koyna finite element model for a series of different linear elastic material properties. Comparisons were made of the natural frequencies calculated in the finite element analysis and the resonant frequencies indicated from the laboratory measurements.

IV.2 Damping Characteristics

A damping factor was estimated from the decay record of measured acceleration after a 0.1 g sinusoidal load was applied to the laboratory model and then removed. It was not possible to instantly stop the motion of the table so this record is not a true free vibration decay record, but it was used to obtain an estimate for the damping factor. This plot is shown in Figure C.3. The logarithmic decrement method and the half-amplitude method were used to calculate a damping factor[2].

A viscous damping factor was calculated using the logarithmic decrement method as:

$$\zeta = \frac{1}{2\pi}\ln\frac{u_P}{u_Q}$$

Where : ζ is the viscous damping factor
u_P is the amplitude at the beginning of a cycle
u_Q is the amplitude at the end of the cycle
(See Figure C.3)

The peak acceleration values selected for u_P and u_Q were 0.13 g and 0.12 g respectively, which resulted in a viscous damping factor of .011.

A viscous damping factor was also calculated using the half-amplitude method as:

$$\zeta = \frac{0.11}{N}$$

Where : ζ is the viscous damping factor
N is the number of periods between points P and R, where the amplitude at point R is half the amplitude at point P.(See Figure C.3)

The number of periods between point P and point R was approximately 7, which leads to a viscous damping factor of 0.016.

Both methods result in a very low damping factor(1 to 2 %). Low level forced vibration field tests on dams typically result in viscous damping ratio's in the range of 1 to 3 percent, while the use of 5 to 10% viscous damping is considered reasonable for dams under large earthquake loading. The use of 5 to 10% viscous damping in the analysis of dams is reasonable because of the existence of vertical contraction joints in the structure which provide a physical damping mechanism. The laboratory model is a solid structure rigidly fixed to the shaking table so a viscous damping ratio of 1 to 2% is reasonable for the analyses in this study.

IV.3 Measured Acceleration and Displacement Time Histories

Figures C.1 and C.2 show the time history plots of accelerations measured during the modal sweep(input record SHAKEA) testing procedure. The displacement time histories measured at the four LVDT's during this laboratory test are shown on Figure C.4. Acceleration time history plots from the second laboratory test, in which the model was shaken to failure(input record SHAKEB), are shown in Figures C.5 and C.6. Displacement time histories from the second shake test are shown in Figure C.7.

IV.4 Final Failure Mode

Figure C.8 shows the final failure surface as it occurred during the SHAKEB laboratory test. Development of a crack through the model and failure occurred very quickly. The test was videotaped using a standard video frame rate of 1/30 of a second. When this film record was reviewed frame by frame after the test it was observed that a failure surface was not visible in one frame and had developed and propagated through the structure by the next video frame. So a through crack developed in less than 0.03 seconds. It was also noted that after initiation of the crack the top of the model began to slide before toppling occurred. The top portion toppled from the model approximately 1 second(14 cycles) after crack propagation began.

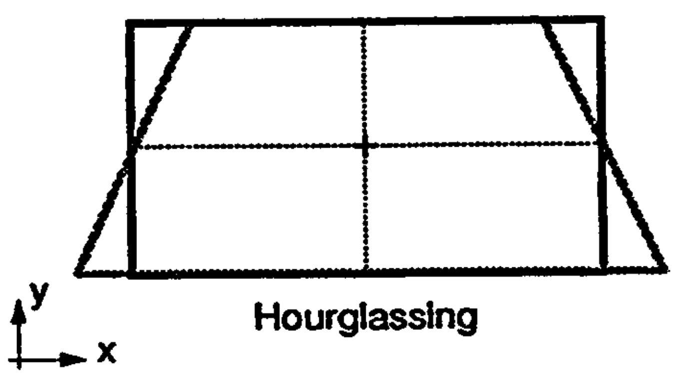
V ABAQUS LINEAR-ELASTIC FINITE ELEMENT ANALYSES

The ABAQUS finite element analysis program has both linear and non-linear analysis capabilities. This portion of the study focuses only on linear elastic dynamic analyses. Performing a linear elastic analysis is the first level of investigation in evaluating the response of a dam-reservoir-foundation system to an earthquake loading. Linear elastic analyses are less expensive than non-linear analyses. While linear elastic analyses cannot predict plastic deformation, crack propagation, or the stress distribution after cracking has occurred, a preliminary linear elastic analysis can to used to calculate natural frequencies and to determine whether or not a non-linear analysis is required through comparison of concrete stress levels with strength properties and to calibratie linear elastic material properties used in a study. Linear elastic dynamic analyses can be performed by using the implicit direct-integration or modal superposition procedures in ABAQUS/Standard[6], or by using an explicit direct-integration procedure in ABAQUS/Explicit[5]. ABAQUS/Standard and ABAQUS/Explicit are separate program modules within ABAQUS. First, modal superposition procedures using ABAQUS/Standard were used for frequency extraction, modal dynamic time history analysis, and response spectrum analyses. The results of these analyses were then compared to the results from an implicit direct-integration dynamic analyses performed using ABAQUS/Standard and an explicit direct-integration analyses performed using ABAQUS/Explicit. Wherever possible the results from each analysis were compared to laboratory measurements. Sensitivity studies were also completed for various analysis parameters, material property parameters and mesh definitions.

V.1 Finite Element Models

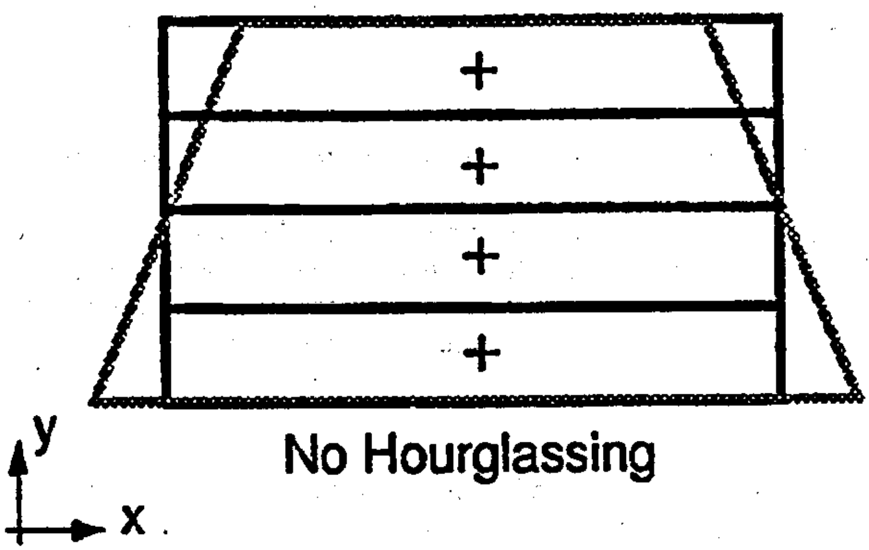
Six different finite element meshes were used in the analyses of the Koyna scale model. All of the analyses use the same three-dimensional solid model which was created to match the physical dimensions of the laboratory model(See Figure B.3). The ABAQUS element type designated "C3D8R" was used in all the models in this study. This is an eight noded, reduced-integration, three dimensional solid brick element with hourglass control. ABAQUS/Standard has a very extensive element library, while the ABAQUS/Explicit element library is more limited. In ABAQUS/Standard fully integrated 3D brick elements are available with both 8 and 20 nodes, in ABAQUS/Explicit only 8 noded 3D brick elements with reduced integration are available. The 8 noded, reduced integration, 3D brick element was selected for this study primarily to facilitate comparisons of results from ABAQUS/Standard and ABAQUS/Explicit in the non-linear analyses to be completed later. The use of tied contact surfaces in ABAQUS was also investigated. A tied contact surface is used to mathematically link two separate finite element models along a common boundary.

The issue of mesh density is particularly important when linear reduced-integration elements are used. These elements can have a numerical charactertistic called "hourglassing". The following figure shows the deformed shape of a linear element with reduced-integration subjected to pure bending. Since this is a linear element with only 8 corner nodes the element edges are not curved, and since this is a reduced integration element it has only one integration point located at the element centroid. When the vertical and horizontal element dimensions are measured through the integration point their length does not change and the angle between them remains 90 degrees in the element's deformed shape. Therefore all of the components of stress at the element integration point are zero and there is no strain energy generated by this element in bending. So if a single linear, reduced-integration element were used through the thickness of a beam model, all the integration points would lie on the neutral axis and the model would be unable to resist bending loads.



Hourglassing

However if enough elements are used through the model thickness then linear reduced-integration elements produce acceptable results in bending. The next figure illustrates the deformed shape resulting when four elements are used through the thickness of a model subjected to bending loads. In this case the horizontal element length measured through the integration point in the top element decreases in the deformed shape indicating that the direct stress in the x-direction(σ_{xx}) is compressive; while the horizontal element length measured through the integration point in the bottom element increases indicating that σ_{xx} is a tensile stress. The angle between a vertical line drawn through all the integration points and horizontal lines drawn through each integration point remain at 90 degrees so the shear stress remains zero. In this case, conditions are consistent with the expected state of stress for pure bending and acceptable results are achieved.



The finite element models varied in element mesh density and orientation. Mesh densities were increased in localized regions of the model around tied contact surfaces. These meshes were identified as Mesh#1, Mesh#2, Mesh#3, Mesh#4, Mesh#5 and Mesh#6. Mesh#1 and Mesh#2 both used tied surfaces to change the mesh density near the change in geometry on the downstream face of the model. Mesh#1 has a finer mesh density than Mesh#2, and the upper tied contact surface is closer to the change in geometry than the tied surface in Mesh#2. The other four mesh definitions do not include any contact surfaces. Meshes #3,#4 and #5 all used a vertical-horizontal mesh orientation with varied densities. Mesh#6 included a sloped mesh orientation. Figures D.1 and D.2 show the six finite element mesh definitions used, while the following table provides a summary of the mesh characteristics.

Table 5 : Finite Element Mesh Definitions			
Mesh Designation	Number of Elements	Number of Nodes	Number of Tied Contact Surfaces
Mesh#1	1470	2102	Two
Mesh#2	484	784	Two
Mesh#3	612	889	None
Mesh#4	2160	2826	None
Mesh#5	84	180	None
Mesh#6	252	410	None

V.2 Boundary Conditions Used For The Finite Element Analyses

The same displacement boundary conditions were used for all of the mesh definitions in this study . All the nodes on the bottom of the model base and on the upstream and downstream faces at and below 23.625 inches were identified as fixed nodes against all three components of translation. The displacement boundary conditions are shown in Figure D.3.

V.3 Loads

The loading sequence used for all of the linear-elastic sensitivity studies was to apply the gravity load in the first analysis step, followed by a frequency extraction step only when modal superposition dynamic procedures were used, and then to apply the laboratory input accelerations to the numerical model in the upstream/downstream direction in the final analysis step. Accelerations were applied at the fixed nodes. Input motion SHAKEA was used for the majority of the linear-elastic analyses because this was a low amplitude acceleration record and therefore the response of the model to this loading was expected to stay well within the linear-elastic range. One second of the SHAKEA acceleration record was extracted from the laboratory data for use in the sensitivity studies. The entire record is approximately 480 seconds long so it was not feasible to analyze the entire record. One second of the SHAKEA record at a point where the frequency was 14 Hz was selected because the entire SHAKEB input acceleration record which will be used for the non-linear analyses has a frequency of 14 Hz.

V.4 Linear Elastic Material Property Model

The ABAQUS linear elastic material model was used for all of the analyses in the first part of this project. The total stress is defined from the total elastic strain as :

$$\sigma = D^{el}\varepsilon^{el}$$

where σ is the total stress, D^{el} is the fourth-order elasticity tensor, and ε^{el} is the total elastic strain. This material model is only valid when the elastic strains are small. The ABAQUS elastic material model can be either isotropic or anisotropic. The low strength concrete mix used in this study was considered to be homogeneous and isotropic. The elastic properties were completely defined by the Young's Modulus(E), and the Poisson's ration(ν).

V.5 Output Locations

Figures D.4 to D.9 show the output locations from ABAQUS used for accelerations and displacements for each of the six meshes used in this study. Each figure shows plan and elevation views of a mesh with the nodes at which accelerations and displacements will be requested as output shown in red. The elevations of these nodes are listed on the figures as well as the elevations at which the instrumentation were actually located on the laboratory model. Therefore these figures provide documentation of how closely the location of the nodes at which output is generated in the ABAQUS analyses match the actual locations of the instructions used in the laboratory for each of the six different mesh definitions.

VI SUMMARY AND CONCLUSIONS FOR INDIVIDUAL LINEAR ELASTIC SENSITIVITY STUDIES

VI.1 Sensitivity of Results to the Number of Modes Extracted in Frequency Analysis

Since both the modal dynamic and response spectrum analysis procedures base the structure's response on a subset of the eigenmodes of the system, the eigenmodes must be extracted prior to running these analyses. The number of modes extracted must be sufficient in each case to model the dynamic response of the system adequately. To determine the number of modes which must be extracted in the frequency analyses for convergence of results in the dynamic analysis, four modal dynamic analyses were completed using 2, 3, 10, and 20 modes. These analyses were completed using Mesh#3, with an elastic modulus of 150 ksi and a material density of 138 pcf.

The resulting accelerations, displacements and CPU times were compared. The results from this sensitivity study are shown in Figures E.1 to E.4. The first three natural frequencies were 15.7, 29.9, and 54.2 Hz. Calculated peak accelerations and displacements are shown on Figures E.1 and E.2. CPU time are also listed on Figure E.1. Acceleration time history plots are shown on Figure E.4.

The results from modal dynamic analyses using from 2 to 10 modes showed only slight differences in peak accelerations and displacements, and the results from analyses using 10 and

20 modes were nearly identical. CPU times ranged from 53 sec, when only 2 modes were extracted, to 210 sec when 20 modes were extracted. CPU times included a static loading step used to apply gravity, the frequency extraction step, and a one second modal dynamic analysis step. The one second input record used was from input record SHAKEA from 279 sec to 280 sec. This section of the SHAKEA input record has a magnitude of 0.1 g and a frequency of 14 Hz.

This study indicated that only the first two modes need be extracted to obtain reasonable results and that results had completely converged when 10 modes were used. Ten modes were extracted and used in the modal dynamic analyses through out the remainder of the linear elastic analysis studies.

VI.2 Sensitivity of Modal Dynamic Results to Variation in Mesh Definition.

The six different finite element meshes were analyzed using the modal dynamic procedure to determine the effects of variations in density, orientation, and the use of tied contact surfaces. Identical linear elastic material properties were used for each of these analyses. The elastic modulus was 150 ksi and the material density was 138.2 pcf. Five percent modal damping was used. One second of input record SHAKEA from 279 to 280 sec was used as the ground motion for these comparisons. Modal characteristics, accelerations and displacements at the locations of instrumentation, energy levels and the CPU times for each analysis were compared.

Figures F.1 to F.12 contain the results of the modal dynamic analyses used to evaluate mesh sensitivity. The modal characteristics were very similar for all the mesh definitions. The first natural frequencies varied from 14.1 Hz for Mesh#5(a very coarse mesh) to 15.7 Hz for Mesh#4(a very fine mesh definition see figure F.1). Accelerations and displacements were also very similar for all the mesh definitions, but they were slightly higher for the coarser mesh definitions. The peak acceleration for Mesh#6(coarse) was 71.4 inch/sec^2, while the peak acceleration for Mesh#4(fine) was 69.4 inch/sec^2. The peak displacement for Mesh#5(coarse) was .0025 inches, while the peak displacement for Mesh#4(fine) was .0021 inches. The CPU time required to complete the analyses varied significantly for different mesh definitions. Fine mesh definitions such as Mesh#1, which also includes two contact surfaces, and Mesh#4, which has a very fine mesh definition with no contact surfaces, required 895 seconds and 446 seconds respectively, while the analysis of Mesh#5, which has a very coarse mesh definition and no contact surfaces, only required 21 CPU seconds. Figure F.1 contains tabulated natural frequencies, peak accelerations and displacements and CPU times from these analyses. Figures F.2 and F.3 show the calculated acceleration and displacement time history plots from the mesh sensitivity study; as well as, the acceleration and displacement time histories measured in the laboratory.

Figure F.4 shows tabulated values for various whole model energy quantities at the end of the static and dynamic load steps for the analyses using each mesh definition. Hourglassing can be a problem with first-order, reduced-integration elements, such as the C3D8R elements used in these analyses. The C3D8R ABAQUS elements include hourglass control, but they should also be used with reasonably fine meshes. ABAQUS monitors the amount of energy spent on controlling hourglassing during the analysis, so the energy levels can be used as an indicator of acceptable/unacceptable mesh density. If the "Artificial" strain energy associated with hourglass control is less than 1% relative to other typical energies then the mesh density is acceptable. From the table on Figure F.4 it is evident that Mesh#1 through Mesh#4 are acceptable based on energy criteria, but Mesh#5 and Mesh#6 are not. The artificial energy levels at the end of the static analysis step for the analysis of Meshes #5 and #6 were 1.1% and 3.5% of the total strain energy, indicating that Mesh#5 and Mesh#6 are too coarsely defined.

A response spectrum analysis was also completed for each of the six mesh definitions using the response spectra generated for input motions SHAKEA and SHAKEB. The results from these analyses were also used to determine the sensitivity of results to mesh density. The maximum principal stresses at all elements were requested as output from these analyses. The material properties used for the response spectrum analyses were an elastic modulus of 210 ksi, a material density of 140 pcf with modal damping at 10 %. A summary of the results from the response spectrum analyses completed for each of the six different mesh definitions is shown in Table 5.

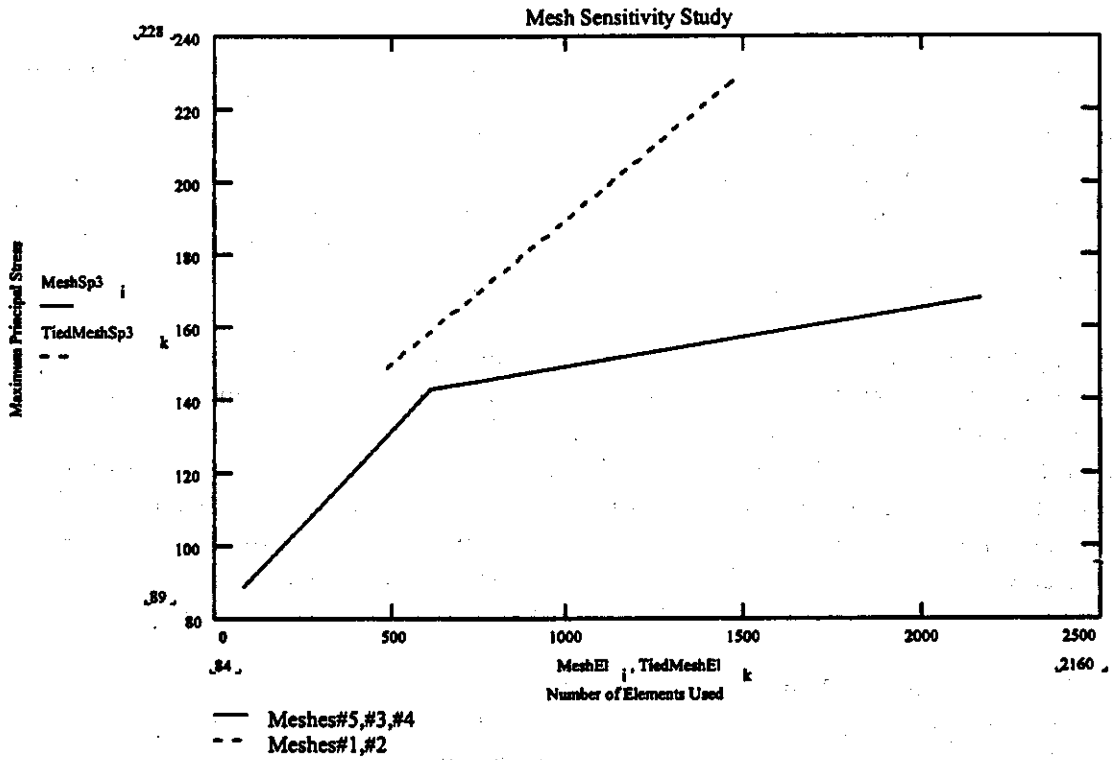
Table 5 : Maximum Principal Stresses from Response Spectrum Analyses

Input : Response Spectrum from SHAKEA						
	Mesh#1	Mesh#2	Mesh#3	Mesh#4	Mesh#5	Mesh#6
SP3	23 psi	15 psi	14 psi	17 psi	9 psi	9 psi
@Elements	Numbers 1369, 1369	Numbers 120, 123	Numbers 282, 330	Numbers 1128, 1288	Numbers 27, 45	Numbers 74, 75
CPU Time	561 sec	109 sec	155 sec	454 sec	18 sec	53 sec
Input : Response Spectrum from SHAKEB						
SP3	228 psi	149 psi	143 psi	168 psi	89 psi	88 psi
@Elements	Numbers 1369, 1369	Numbers 120, 123	Numbers 282, 330	Numbers 1128, 1288	Numbers 27, 45	Numbers 74, 75
CPU Time	565 sec	109 sec	155 sec	456 sec	18 sec	53 sec

Figures F.5 and F.6 show the location of the elements at which the maximum principal tensile stresses occurred in response to the SHAKEA spectrum input for the six different mesh definitions. The plot of Mesh#1 indicates that the elements at which the maximum principal stress occurred were located on the downstream face adjacent to, and directly above, the change in slope. These two elements are also adjacent to, and directly below, the upper tied contact surface. For the other five mesh definitions the elements at which the maximum principal tensile stress occurs are located adjacent to, and directly below , the change in slope on the downstream face of the model. Figures F.7 and F.8 show the maximum principal tensile stress contour plots from these response spectrum analyses. The contour plots of Mesh#1 and Mesh#2 both show a sudden jump in the stress levels at the tied contact surfaces. Mesh#1 produced the highest maximum principal tensile stress(23 psi), but these peak stresses appear to be associated with the change in mesh density occurring on the upper tied surface. In mesh#2 where the upper tied surface was moved farther away from the location of the change in slope on the downstream face the maximum principal stresses occurred at the change in slope and were reduced to 15 psi which seems much more reasonable. All of the contour plots indicate that the maximum principal tensile stress occurs on the downstream face near the change in slope, but stress results from the fine mesh definitions were significantly higher. The maximum principal stress from the analysis of Mesh#4 was 17 psi while the maximum principal stress resulting from the analysis of Mesh#5 was only 9 psi. Use of a coarser mesh definition resulted in a 47 percent under-estimate of the maximum principal stress, because the stress output location is farther away from the stress concentration at the change in slope.

Figures F.9 through F.12 show the locations of elements in which the maximum principal tensile stresses occur, and the maximum principal tensile stress contour plots from the response spectrum analyses using the spectrum from input motion SHAKEB. These results are similar to the results obtained using input motion SHAKEA. The maximum principal stress distributions are the same with increased magnitudes. Once again a significant increase in the maximum principal stress was seen in Mesh#1 where the tied surface was positioned near the change in slope on the downstream face. The maximum principal stress occurring in Mesh#1 was 228 psi, while the maximum principal stress occurring Mesh#2 was 149 psi.

The response spectrum results using the spectrum from SHAKEB also show a 47 percent reduction in stress between Mesh#4 with a maximum principal stress of 168 psi and Mesh#5 with a maximum principal stress of 89 psi. The following plot shows the maximum principal stresses from the response spectrum analyses for spectrum SHAKEB plotted against the number of elements in the mesh.



Results from Mesh#1 and Mesh#2 are plotted separately using the dashed curve since these mesh definitions include tied surfaces. Meshes #3,#4, and #5 are shown with a solid curve. The plot shows maximum principal stress values converging as the mesh density increases with the exception of the results from Mesh#1. The maximum principal stresses resulting from the analysis of Mesh#1 appear to be associated with the location of the tied surface and are therefore considered to be invalid. There was a considerably more gradual increase in maximum principal stress value between Mesh#3(612 elements) and Mesh#4(2160 elements) than between Mesh#5(84 elements) and Mesh#3, but there was also an 273 percent increase in CPU time between analyses using Mesh#3 and Mesh#4.

The results of the mesh sensitivity study indicate that the quantities calculated at nodes, such as accelerations and displacements, are not extremely sensitive to mesh definition, however the stress values calculated at the element integration points were sensitive to changes in mesh density, with substantial underestimation of stress resulting from the use of mesh definitions that are too coarse. Energy terms are also a useful tool in determination of acceptable mesh density. Mesh#3 was selected for use in the rest of the linear elastic sensitivity studies in this report since it provided a reasonable combination of degree of convergence of results, relatively short CPU time, and acceptable energy levels.

VI.3 Sensitivity of Results to Variations in Linear-Elastic Material Properties

To determine the sensitivity of results to variations in material and damping parameters a series of modal dynamic analyses were performed. The resulting acceleration and displacement time histories were compared with laboratory measurements. In the first set of analyses only the elastic modulus was varied. Analyses using elastic moduli of 90, 113, 120, 130, 157, 200, 300, and 350, ksi were included. For this first set of analyses the modal damping option was used with the damping set at 3.5% of critical damping. The material density was 138.2 lb/ft^3. The value 138.2 lb/ft^3 is the density of this material as determined in the laboratory.

Figure G.1 shows the natural frequencies obtained from this set of analyses. These analyses resulted in a fairly linear increase in the natural frequency with increased elastic modulus. The first natural frequencies varied from 12.1 Hz for a elastic modulus of 90 ksi to 23.9 Hz for an elastic modulus of 350 ksi. The second natural frequencies varied linearly from 23.2 Hz for a elastic modulus of 90 ksi to 45.74 Hz for an elastic modulus of 350 ksi. The first natural frequencies obtained using a material density of 138.2 pcf best match the laboratory test predictions when the elastic modulus used was approximately 200 ksi. This material property set resulted in a first natural frequency of 18 Hz and a second natural frequency of 35 Hz.

Figures G.2 and G.3 show tabulated and plotted peak acceleration and displacements for this series of analyses. Acceleration and displacement time history plots are shown in figures G.4 and G.5. The calculated accelerations and displacements approached the peak values measured in the laboratory experiment as the elastic modulus increases, with the best match occurring for an elastic modulus between 300 and 350 ksi. The elastic modulus which produced best overall match for natural frequencies, accelerations and displacements was between 200 and 300 ksi.

In the second set of analyses the input acceleration frequency was varied. Analyses using elastic moduli of 113, 157, 200, ksi were re-analyzed using input records with frequencies of 6, 10, 14, 18, 20, 22, 24, and 26 Hz. These input records were extracted from the SHAKEA input record. For this set of analyses the modal damping and material density were the same as in the first set of analyses. The Rayleigh damping was set so that the majority of the frequencies wee damped at 3.5% of critical damping, and the material density was 138.2 lb/ft^3. The natural frequencies obtained from this set of analyses were the same as those obtained from the first set of analyses, which are shown in figure G.1. The first natural frequencies best match the laboratory test predictions when the elastic modulus used was approximately 200 ksi.

Figures G.6 and G.7 show tabulated and plotted peak horizontal accelerations resulting from this series of analyses. Figure G.8 shows the tabulated and plotted peak vertical acceleration for this series of analyses. Figures G.9 and G.10 show the peak displacements. Acceleration and displacement time history plots are shown in figures G.11 through G.28.

The peak upstream-downstream accelerations generated by ABAQUS, for analyses using input frequencies of 14 Hz or greater, approached the peak values measured in the laboratory experiment as the elastic modulus was increased(E > 200 ksi). The laboratory values tended to be lower than the results produced by the analyses and the results produced by the analyses tended to decrease as the modulus was increased.

The peak vertical accelerations measured in the laboratory for input frequencies of 20 Hz or less tended to be significantly higher than the values produced by the analyses. The ABAQUS values for the vertical acceleration at the top of the model tend to increase as the modulus is decreased, therefore the analyses using lower moduli(E < 113 ksi) best match the measured values. For input frequencies of 22 Hz or greater this trend is reversed with the higher moduli producing the best match with the laboratory measurements.

The peak upstream-downstream displacements measured in the laboratory tended to be lower than those calculated in the analyses. The ABAQUS values decreased as the modulus increased producing the best match for higher moduli(E > 200 ksi).

The upstream-downstream acceleration time history plots showed that at low input frequencies (6 and 10 Hz) the results are less sensitive to the value of elastic modulus used. The acceleration results from ABAQUS matched the laboratory curves equally well over all three moduli. However, the results were sensitive to the modulus used in the analyses with input frequency of 14 Hz or greater. In the analyses using input acceleration of 14 Hz or greater the ABAQUS results consistently most closely matched the laboratory values when an elastic modulus of 200 ksi was used.

The vertical acceleration time history plots showed that the laboratory values were significantly higher than the ABAQUS values for input frequencies of 14, 18, and 20 Hz. These input frequencies bracket the natural frequency of the structure(18 Hz). It may be that the boundary conditions in the laboratory did allow for some vertical movement at the base of the model which was not accounted for in the analysis. When input frequencies of 22 and 24 Hz were used the ABAQUS analyses using ana elastic modulus of 157 were the best match to the laboratory measurements, while the analyses using a 26 Hz input motion best matched the laboratory values when a modulus of 200 ksi were used.

The upstream-downstream displacement time history plots for input frequencies of 6, 10 and 14 Hz show the best match when the modulus is increased(E > 200 ksi). When an 18 Hz input motion was used a 180 degree phase shift developed between the ABAQUS curves and the displacement time history curve from the laboratory measurements, although the amplitudes still matched best when a modulus of 200 ksi was used. Again this is an indication that the boundary conditions in the laboratory were not completely captured in the analyses. The plots of displacement time history records for input frequencies of 20 Hz and greater are back in phase with the best match in terms o f amplitude resulting from the analyses using an elastic modulus of 200 ksi.

In the third set of analyses only the material density was varied. Analyses using a material density of 100, 138.2 and 200 lb/ft^3 were included. The amount of modal damping used was 3.5% of critical damping. The three densities were analyzed for each of the following elastic moduli : 113, 157, 200, 300 and 350 ksi.

The natural frequencies from these analyses are shown in figures G.29 to G.33. The first natural frequencies calculated using an elastic modulus equal to or less than 157 ksi approached 18 Hz when the material density was decreased, while the analyses using an elastic modulus greater than 157 ksi approached 18 Hz when the material density was increased. Interpolation of these results indicates that each of the following material property combinations would result in first natural frequencies of exactly 18.0 Hz :

Elastic Modulus	Material Density	First Natural Frequency	Second Natural Frequency
113 ksi	68 pcf	18.0 Hz	34.4 Hz
157 ksi	111 pcf	18.0 Hz	34.5 Hz
200 ksi	140 pcf	18.0 Hz	34.6 Hz
300 ksi	207 pcf	18.0 Hz	34.4 Hz
350 ksi	228 pcf	18.0 Hz	34.5 Hz

Plots of the mode shapes obtained from three of these analyzes are shown in Figures G.34 through G.36. These plots show that the first mode is a cantilever mode acting in the cross-canyon direction, while the second mode is a cantilever mode acting in the upstream-downstream direction.

Figures G.37 through G.46 show tabulated and plotted peak accelerations and displacements for the series of three analyses completed for each of five elastic moduli where the density was varied(100, 138.2, and 200 pcf). In each set of analyses the peak values from the analyses more closely approach the peak values measured in the laboratory when the material density was decreased. Figures G.47 to G.51 show acceleration time history plots. Each plot shows four acceleration time histories, one curve for each of the three densities analyzed for a given elastic modulus plus the acceleration time history measured in the laboratory. Each figure contains four such plots, one for each of the four horizontal accelerometers on the model. These plots show that the accelerations decrease with decreased material density independent of the elastic modulus, and that the accelerations decrease as the elastic modulus increases independent of material density.

The average value for the elastic modulus determined from the static compression tests was 157 ksi, while the average value for the elastic modulus resulting from rapid compression tests was 113 ksi. A decrease in dynamic modulus compared to the static modulus was unexpected. Typically the dynamic modules is equal to or greater than the static modulus. The current practice at Reclamation for the static finite element analysis is to reduce the average elastic modulus determined from the static compression test by a factor of one third to account for long term creep(E_{static} =105 ksi), and to increase the average elastic modulus from the static compression test by a factor of four-thirds for use in the dynamic finite element analyses($E_{Dynamic}$ = 209 ksi). Reclamation is currently performing rapid compression tests on all concrete core to develop a database of static and dynamic properties.

Dr. Jerome Raphael's paper "Tensile Strength of Concrete" published in the ACI Journal in 1984,[8] reported on tensile and compressive strength testing on concrete specimens which resulted in the conclusion that the rate of loading characteristic of an earthquake increases compressive strength an average of 31 percent and increases tensile strength an average of 56 percent.

The results of this sensitivity study show that any number of combinations of the two linear elastic material properties (elastic modulus and material density) could be used to obtain modal characteristics matching those produced in the free vibration test. It is recomended that the modulus be varied because the calculation of density using volume and weight measurements of a material specimen is very straight forward and are expected to be quite accurate. The measured density of 138.2 pcf is probably accurate within ± 5 pcf.

Selection of the dynamic elastic modulus is much less certain. Comparisons of natural frequencies resulting from the modal dynamic ABAQUS analyses and the resonant frequencies identified from the measured acceleration and displacement time histories suggest that the most appropriate elastic modulus would be approximately 200 ksi. Comparison of accelerations and displacements resulting from the modal dynamic analyses and the accelerations and displacements measured in the laboratory suggest that the most appropriate elastic modulus would be between 200 and 300 ksi. The value which would be selected based on current practice at the Bureau is 210 ksi. Therefore the results from the current study tend to support current practice of increasing the static modulus for use in dynamic analyses.

VI.4 Variation in the Amount of Damping Included in Modal Dynamic Analyses

In the this set of analyses the modal direct damping option was used which allows the same damping for each mode. Only the percent of critical damping used was varied. Analyses were completed for the following material properties:

Linear Elastic Material Property set #1) E = 190 ksi and γ = 133 pcf,

Linear Elastic Material Property set #2) E = 200 ksi and γ = 140 pcf,

Linear Elastic Material Property set #3) E = 210 ksi and γ = 140 pcf,

Linear Elastic Material Property set #4) E = 250 ksi and γ = 140 pcf.

The analyses for each material property were repeated for different percentages of critical damping to determine how much damping would influence the resulting acceleration and displacements and to determine how much damping would be required for the resulting acceleration and displacements to match those measured in the laboratory experiment. The modal damping percentages used were 3.5%, 5%, 10%, 38%, and 88%. Peak values of acceleration and displacement, acceleration and displacement time histories, natural frequencies, and CPU times were compared.

The first three natural frequencies for each material property are shown on Figure H.1. The first natural frequencies for these material property sets are approximately 18 Hz, with the exception of material property set #4 which had a first natural frequency of 20 Hz. The material density for material property set #4 would have to be increased an unrealistic amount to maintain a first natural frequency of 18 Hz. Peak values of acceleration and displacement, as well as the CPU time required to complete each analysis, are shown in Figures H.2 through H.9. These results indicate that the percent damping used has relatively little affect on the accelerations and displacements. At least 88 percent of critical damping would be required for the peak values from these analyses to converge exactly with the values measured during the shake test. This was true for all four material property sets. Acceleration and displacement time history plots are shown on Figures H.10 through H.17. These results show that while it may require an unrealistic amount of damping to match the measured accelerations exactly, the curves generated from all of these analyses actually match the measured values fairly well for all levels of damping. It is also notable that a phase shift develops in the displacement time history curves at damping levels equal to or greater than 38 percent. The analyses using damping levels less than 38 percent are not as good a match with respect to the peak magnitudes, but they are a much better match in phase. The amount of damping did not have a significant effort of the CPU time required to run the analyses. CPU time only varied from 267 to 278 seconds.

VI.5 Variation in Selection of Damping Method in Modal Dynamic Analyses

In this set of analyses only the damping method was varied. Modal dynamic analyses were completed using three damping methods : direct, Rayleigh, and composite. Only the method of applying the damping was varied. For this set of analyses the elastic modulus was 210 ksi, and the material density was 138.2 lb/ft^3. Accelerations, displacements and CPU times were compared.

The first damping method was "direct" modal damping. When the direct method is used the damping in each eigenmode is given as a fraction of the critical damping for that mode. The equation of motion for a one of the eigenmodes of the system is given as:

$$m\ddot{q}+c\dot{q}+kq=0$$

Where m is the mass, c is a damping factor, k is the stiffness and q is the modal amplitude. The solution is of the form

$$q=A\exp\lambda t$$

Where A is a constant, and

$$\lambda = -\frac{c}{2m} \pm \sqrt{\frac{c^2}{4m^2} - \frac{k}{m}}$$

If the expression under the root sign is negative the solution will be oscillatory(under damped). Critical damping is defined as the damping value which makes the expression under the root sign equal to zero or

$$c_{cr} = 2\sqrt{mk}$$

When an acceleration load is removed from a critically damped system there will be no oscillation, the amplitude will decay very rapidly. For these analyses 10% of the critical damping level was applied to each of the first three modes, and only the first three modes were considered in the analysis. Since this damping method associates the damping with the eigenmodes of the system, this damping method can not be used in the nonlinear dynamic analysis procedures where the equations of motion of the system are integrated directly, and the natural frequencies of the system are constantly changing.[6][2]

The second damping method was "Rayleigh" damping. When the Rayleigh damping method is used the damping is defined using a damping matrix([C]). This damping matrix is a linear combination of the mass and stiffness matrices:

$$[C] = \alpha[M] + \beta[K]$$

Where α is the mass damping factor and β is the stiffness damping factor. In ABAQUS standard modal dynamic analysis procedures Rayleigh damping is converted into critical damping fractions for each mode. The α and β damping factors are defined independently for each mode included in the analysis. For each mode$_i$ the fraction of critical damping is given as :

$$\xi_i = \frac{\alpha_i}{2\omega_i} + \frac{\beta_i \omega_i}{2}$$

For this analysis the equation above was entered in a MathCadd spreadsheet and then α and β factors were selected such that 10 percent critical damping was used for the first three modes as follows:

$\alpha_i :=$	$\beta_i :=$	$\omega_i :=$	ξ_i
3.4	.0008	18.4	0.1
6.4	.0005	35.2	0.1
9.5	.0008	63.6	0.1

[6]

The third modal damping method was "composite" damping. When composite damping is used a damping value can be defined for each material in the model. The amount of dampening is entered as a fraction of critical damping. These values are then converted into a weighted average for each eigenmode. In this analysis there is only one material property set used for the entire model, so only one damping value was used: 10 percent of critical. The first three modes were included in the analysis. When this method is used the damping ratio is defined as:

$$\xi_\alpha = \frac{1}{m_\alpha} \Phi_\alpha^M \xi_m M_m^{MN} \Phi_\alpha^N$$

Where ξ_α is the critical damping ratio used in mode α; ξ_m is the critical damping fraction defined for material m; M_m^{MN} is the mass matrix associated with material m; ϕ_α^M is the eigenvector of the α th mode; and m_α is the generalized mass associated with the α th mode. This equation is summed over all the materials for each mode. In this study the model has only one material, so the equation reduces to defining the critical damping ratio for each mode as in the direct damping method. In this case a 10 percent damping ration was used for the first three modes and only three modes were included in the analysis.[6]

Figures H.18 and H.19 show the peak accelerations and displacements from these analyses, while Figures H.20 and H.21 show the acceleration and displacement time histories. The accelerations and displacements resulting from the analyses using modal and composite damping were identical as they should be since there is since the model includes only one material. The results from the analysis using Rayleigh damping were also nearly identical. The CPU times were also nearly the same for all three analyses. These results simply verify that all three modal damping methods will produce the same results when the same amount of damping is specified, as they should.

VI.6 Sensitivity of Results to Variation Analysis Time Increment

Two sensitivity studies were completed to determine the effect of analysis parameters controlling the analysis time step in direct-integration dynamic analysis procedures. When the modal dynamic analysis method was used the selection of the appropriate time step was very straightforward. The time increment used in the dynamic procedure was selected to match the time increment of the seismic input record. Input accelerations were assumed to vary linearly between these values. There are two methods of controlling the analysis time increment available when the implicit direct-integration dynamic analysis procedure is used.

The first method is direct user control of increment size, in this case the increment is entered in the input file and can not change during the analysis. This method is not recommended because when the direct time incrementation parameter is used the time increment can not be reduced to obtain a converged solution. In this case, if convergence is not achieved within the maximum number of iterations allowed in the program the analysis stops. It would be particularly difficult to select a constant time increment for a nonlinear dynamic analysis. The first sensitivity study involving the analysis time increment was completed to determine the effect of varying the analysis time increment using the direct time increment parameter. Three linear-elastic direct integration dynamic analysis were completed using analysis time increments of .0001, .003, and .01 seconds. One second of the input record SHAKEA, from 279 to 280 seconds, was used as input accelerations for these analyses. The material properties used in these analyses were an elastic modulus of 210 ksi and a material density of 140 pcf. Rayleigh material damping was used in these analyses, with $\alpha = 8.936$ and $\beta = .000132$(10% of critical). Accelerations and displacements were compared.

Figures I.1 and I.2 show the peak acceleration and displacement values for the three analyses in which the time increment was varied, while Figures I.3 and I.4 show the acceleration and displacement time histories. The results show that the accelerations and displacements calculated in the ABAQUS analyses do more closely match the measured values as the time increment decreases, but the values shown for the CPU time required to complete the analyses showed a marked increase in computation time as the time increment was reduced. When a .01 second time increment was used the required CPU time was 557 seconds(≈10 minutes). This is more CPU time that was required in any of the modal dynamic analyses, but is still not an unreasonable time period. When the time increment was decreased to .003 seconds the CPU time increased to 1441 seconds(≈24 minutes). When the time increment was further decreased to .0001 sec the CPU time was 39564 seconds(≈11 hours).

The CPU times reported here are the time used when the workstations CPU was actually working on this job. The workstation used for this study was far from a single user machine. When several jobs are running on the system at the same time the CPU cycles through them; they share the processing time. As a result during the course of this study processes reporting CPU times of ≈557 seconds actually took ≈24 hours to complete, and jobs requiring 11 hours of CPU time actually took 4 or 5 days to complete. Therefore considering the amount of improvement in the results and the additional time required when the analysis time increment was decreased, a time increment of .01 seconds was considered satisfactory for this analysis.

The second method of controlling the analysis time increment is to use the "Haftol" parameter for the automatic time incrementation scheme. The Haftol parameter is set equal to the half-step residual tolerance. The Haftol parameter has dimension of force and can be chosen by comparison with typical actual force values, such as applied forces or expected reaction forces. The ABAQUS program manual offers the following guidelines : " For problems where considerable plasticity or other dissipation is expected to damp out the high frequency response, choose Haftol as 10 to 100 times typical actual force values for moderate accuracy and low cost; choose Haftol as 1 to 10 times typical actual force values for higher accuracy. For elastic cases with little damping Haftol values should be smaller than recommended above. Choose Haftol as 1 to 10 times typical actual force values for moderate accuracy; choose Haftol as 0.1 to 1 times actual force values for higher accuracy."[5][6] In dynamic analyses the typical(average) force applied to the structure is not always obvious. In the case of the Koyna laboratory model study a value for the applied force could be approximated as the mass of the model(17.16 slugs) times the peak acceleration of input record SHAKEA(38.64 in/s^2), which results in a value of 663 pounds force. Therefore the use of a Haftol parameter equal to 60 to 600 should produce accurate results for the linear elastic analyses. When the Haftol parameter is selected the program uses an automatic time incrementation method. In this case the program monitors the equilibrium residual error(out-of-balance forces) halfway through each time increment and adjusts the time increment accordingly. So if the "half-step residual" is small, it indicates that the accuracy of the solution is high and the time step is automatically increased. If the half-step residual is large, then the time step used in the solution is automatically reduced.

In this study the Koyna model, using Mesh#3 with an elastic modulus of 210 ksi and a material density of 140 pcf, was analyzed using three different values for the Haftol parameter: 5, 50, and 500. Accelerations, Displacements and CPU times were compared. Figures I.5 and I.6 show the peak acceleration and displacement values resulting from these analyses. Figures I.7 and I.8 show the acceleration and displacement time histories. Again the resulting peak accelerations and displacements more closely approach the measured values as the Haftol parameter is reduced, but the CPU time was also greatly increased. The CPU time required when the analysis was completed using a Haftol parameter of 500 was 785 seconds(≈13 hours), while the CPU time required when the analysis was completed using a Haftol parameter of 5 was 3179 seconds(≈53 hours).

VI.7 Comparison of Modal, Implicit and Explicit Dynamic Analyses Procedures

In the ABAQUS finite element program there are several procedures available for performing dynamic analyses, three of which are the modal, implicit and explicit dynamic analysis procedures. The modal dynamic procedure calculates dynamic time history response for linear problems using the principals of modal superposition. A frequency extraction must be performed prior to performing the modal dynamic analysis since the structures's response is based on the natural modes of the system. As long as the system is linear and is represented correctly by the modes being used the method is very accurate and is usually less expense than the direct integration methods. The implicit dynamic analysis procedure(available in ABAQUS/Standard) and the explicit dynamic analysis procedure(available in ABAQUS/Explicit) differ in the choice of operator used to integrate the equations of motion. The implicit procedure uses the Hilber-Hughes-Taylor operator, which must be inverted and a set of simultaneous linear(or non-linear) dynamic equilibrium equations must be solved at each time increment. This is done iteratively using Newton's method. This can be computationally expensive, but it has an advantage in that the Hilber-Hughes-Taylor operator is unconditionally stable for linear systems so there is no upper limit on the time increment size. In the implicit procedure the dynamic qualities solved at time ($t + \Delta t$) are based both on their values at t and on their values at ($t + \Delta t$). On the other hand, the explicit dynamic analysis procedure obtains the values for dynamic quantities at ($t + \Delta t$) based entirely on available values at time t. Displacement and velocities are calculated in terms of quantities that are known at the beginning of an increment, the global mass and stiffness matrices need <u>not</u> be formed and inverted as in the implicit integration scheme, therefore the explicit procedure tends to be less expense. The explicit method uses a central difference operator for integration of the equations of motion. The central difference operator is only conditionally stable, the stability limit being approximately equal to the time required for an elastic wave to cross the smallest element dimension in the model.[5][4]

In this study the Koyna monolithic model was analyzed using each of these three methods. One second of the SHAKEA input record(279 to 280 seconds) was used for the dynamic loading. The elastic modulus was 210 ksi and the density was 140 pcf. The resulting accelerations, displacements and required CPU times were compared. Figures J.1 and J.2 show the peak accelerations and displacements. Figures J.3 and J.4 show the acceleration and displacement time histories. The peak accelerations and displacements were very similar from all three analyses. The CPU times required for the Modal and Explicit analyses were similar, 264 seconds and 203 seconds respectively, while the required CPU time for the Implicit analysis was much longer(3179 seconds).

VII. NON-LINEAR ANALYSES

A thorough investigation of the concrete non-linear material properties is beyond the scope of this report. The following non-linear mesh sensitivity study is presented here only for comparison with the linear elastic mesh sensitivity study. There were two issues evaluated in this study. The first was to determine to what extent tied contact surfaces, used to change mesh density, influence results in a non-linear concrete cracking analysis. The second was to determine the sensitivity of cracking predictions to variation in mesh density where no contact surfaces were used.

The ABAQUS/Explicit dynamic analysis procedure was used for this study. Four different meshes were used to analyze the uncracked Koyna model. The first meshes used tied contact surfaces to change the mesh density near the area where cracking was expected to occur(Mesh#1 and Mesh#2), while the third and fourth meshes(Mesh#3 and Mesh#5) used no contact surfaces. The same material properties, boundary conditions and loads were used for these three analysis. Each model was analyzed to the point at which complete failure of the structure occurred. Cracking patterns, times at which failure was predicted were compared to laboratory observations of the test in which the monolithic (uncracked) Koyna model was shaken to failure.

A static gravity load was applied in the first second followed by a 280 second dynamic loading. The 14 Hz sinusoidal input motion, which was used to shake the laboratory model to failure (Record SHAKEB), was used for these comparisons. The input acceleration was applied in the upstream-downstream direction only. The entire laboratory test input record is 480 seconds long. For this comparison only the last half of the record was used(from 200 to 480 seconds). The amplitude of the input motion is 1.2 g at 200 sec and increases in steps of 0.2 g approximately every 25 seconds.

Cracking patterns, time of crack initiation, and time of model failure are shown in figures K.1 through K.4 for each of the four mesh definitions. Mesh#1 resulted in crack initiation at 206 sec, which is very early in the input record considering that the laboratory model cracked and then reached failure at around 480 sec. Figure K.1 also shows that the cracks developed along the tied contact surfaces. The analysis of Mesh#1 reached a complete failure at 212 sec. Mesh#2 resulted in crack initiation at 222 seconds, which was also premature. Figure K.2 shows that the crack pattern developed along the tied contact surfaces even when the tied surface was moved farther away from the change in slope on the downstream face. The analysis of Mesh#2 reached completed failure at 235 seconds. Mesh#3 resulted in crack initiation at 401 seconds, which seems much more reasonable. Cracking developed first on the downstream face at the change in slope, then proceeded through the model in the upstream-downstream direction curving downward slightly until the upstream face was reached at 402 seconds and failure was indicated. This cracking pattern is very reasonable and compares well to laboratory observations. Figure C.8 shows the cracking pattern which resulted from the laboratory test.

The results of this study indicate that tied surfaces should not be used for any non-linear cracking analysis of concrete structures. Stress concentrations appear to develop along the tied surfaces causing cracks to develop which would not occur in a model without tied surfaces under the same loading conditions. The two mesh definitions without tied surfaces produced very similar results in terms of both the time of crack initiation and crack orientation. These results suggest that a fairly coarse mesh can be used to analyze non-linear concrete cracking in the ABAQUS/Explicit program.

VII CONCLUSIONS AND RECOMMENDATIONS

1) The linear elastic material properties of the monolithic Koyna model were successfully calibrated primarily through comparisons of natural frequencies, as calculated in the ABAQUS finite element code, and the resonant frequencies identified from the measured acceleration time history records, and secondarily, through direct comparisons of calculated and measured accelerations and displacements. The most appropriate linear elastic material property set consisted of a dynamic modulus equal to 210 ksi with a material density equal to 140 pcf. The results of this study confirmed that it is very important that the most appropriate value for the dynamic modulus be identified for use in analyzing dams under seismic loading, since the dynamic modulus greatly influences the results. The reason for the decrease in modulus observed in the rapid compression test values still needs to be understood. Whenever forced vibration tests at a dam are available their results should be used to calibrate/verify the value concrete modulus used for the dynamic analysis regardless of whether linear elastic or non-linear analysis methods will be used.

2) The analysts choice of mesh definition also has a significant effect on results. The use of tied contact surfaces to vary mesh density in localized regions is not recommended for either linear elastic or nonlinear cracking analyses. Stress concentrations tend to develop along the tied contact surfaces. It may be possible to effectively use tied contact surfaces for linear elastic analyses providing that the they are positioned relatively far away from areas of interest, but they should not be used in non-linear analyses where cracking is important. Variables calculated at element integration points, such as stresses and strains, are sensitive to mesh density regardless of whether or not tied surfaces are included in the mesh design. Stress levels may be significantly underestimated if too coarse of a mesh definition is selected. Mesh density studies can be used to determine the minimum required density for convergence of results, but the time involved in conducting such studies is often a limiting factor. Therefore the energy terms are a particularly useful tool for determination of acceptable mesh density.

3) Selection of a an appropriate analysis time increment size is also critical to obtaining reliable results in a reasonable time frame. It is recommended that the Haftol parameter be used to allow the program to automatically select the analysis time increment, except when the modal dynamic procedure is used in which case the time increment of the input record should be used as the analysis increment. Sensitivity studies may still be required to determine the appropriate force tolerance value for a given analysis even when the automatic time increment option is used, but these could be completed using a very short time period selected from the input record.

4) The ultimate goal of the shaking table test program is to develop a correlation between the material testing program and the material property requirements of the non-linear numerical concrete cracking model used in the ABAQUS finite element code. In the current phase of the project the linear elastic material properties were successfully calibrated and the effects of various mesh configurations and analysis parameters were investigated. In future work, development of the nonlinear material properties required needs to be completed.

References

1 ASTM C39, "Test Method for Compression Strength of Cylindrical Concrete Specimens", and ASTM C469, "Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete Compression". Annual Book of ASTM Standards, Vol 4.02, American Society for Testing and materials, West Conshohocken, PA, 1997.

2 Craig, Roy, Structural Dynamics, An Introduction to Computer Methods, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, John Wiley and Sons, New York.

3 Duron, Ziyad and Hall, John, "Experimental and Finite Element Studies of the Forced Vibration Response of Morrow Point Dam",Earthquake Engineering and Structural Dynamics, Vol. 16, pages 1021-1039, 1988.

4 Kincaid, David, Numerical Analysis, Mathematics of Scientific Computing, The University of Texas at Austin, Brooks/Cole Publishing Company, 1991.

5 Hibbitt, Karlsson and Sorensen, Inc, ABAQUS/Explicit User's Manual, Version 5.7, Pawtucketet, RI

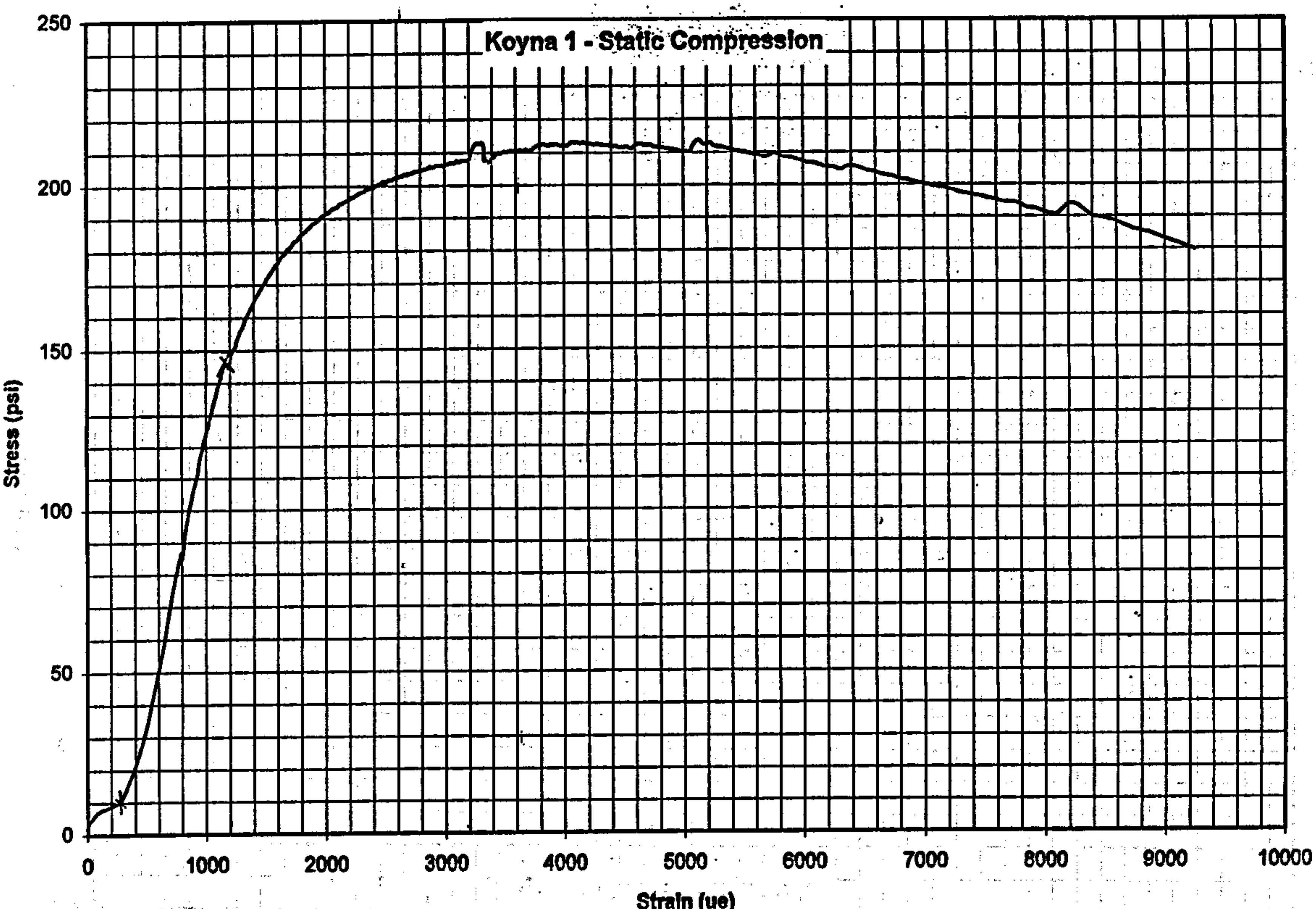
6 Hibbitt, Karlsson and Sorensen, Inc, ABAQUS/Standard User's Manual, Version 5.7, Pawtucketet, RI

7 Niwa, Akira and Clough, Ray, "Shaking Table Research on Concrete Dam Models" Report No. UCB/eerc 80-05, Earthquake Engineering Research Center University of California, Berkeley, CA, 1980.

8 Raphael, Jerome, "Tensile Strength of Concrete", ACI Journal Title No. 81-17, March-April 1984.

9 Harris, David; Snorteland,Nathan and Dolen,Timothy,"Shakeing Table 2-D Models of Concrete Gravity Dam for Computer Code Validation",U.S. Bureau of Reclamation, Materials Engineering and Research Laboratory, Denver, Co.

Appendix A
Laboratory Material Property Test Results



$$\frac{147 - 10}{1150 - 275} = .16 \times 10^{6}$$

Figure a1

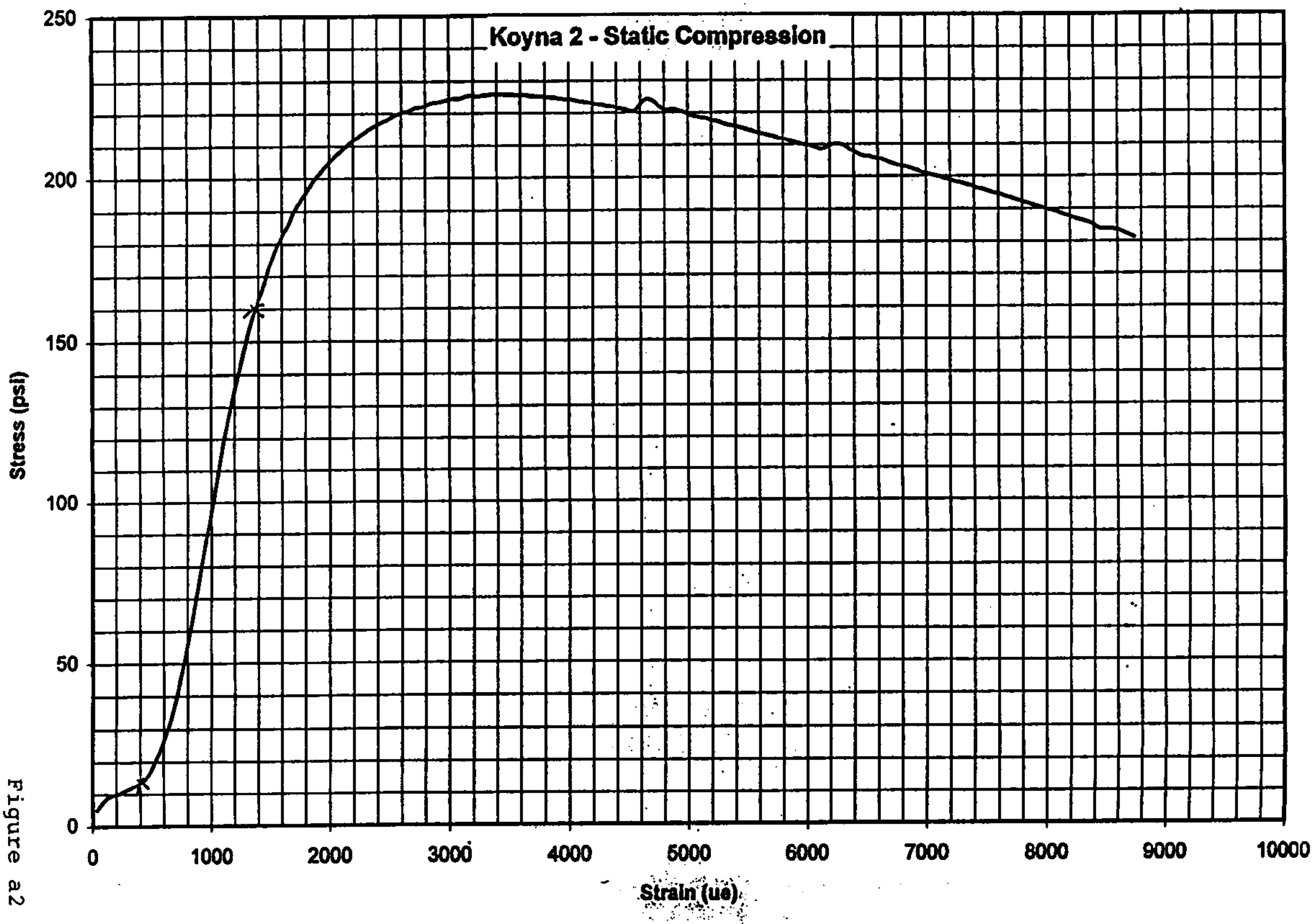
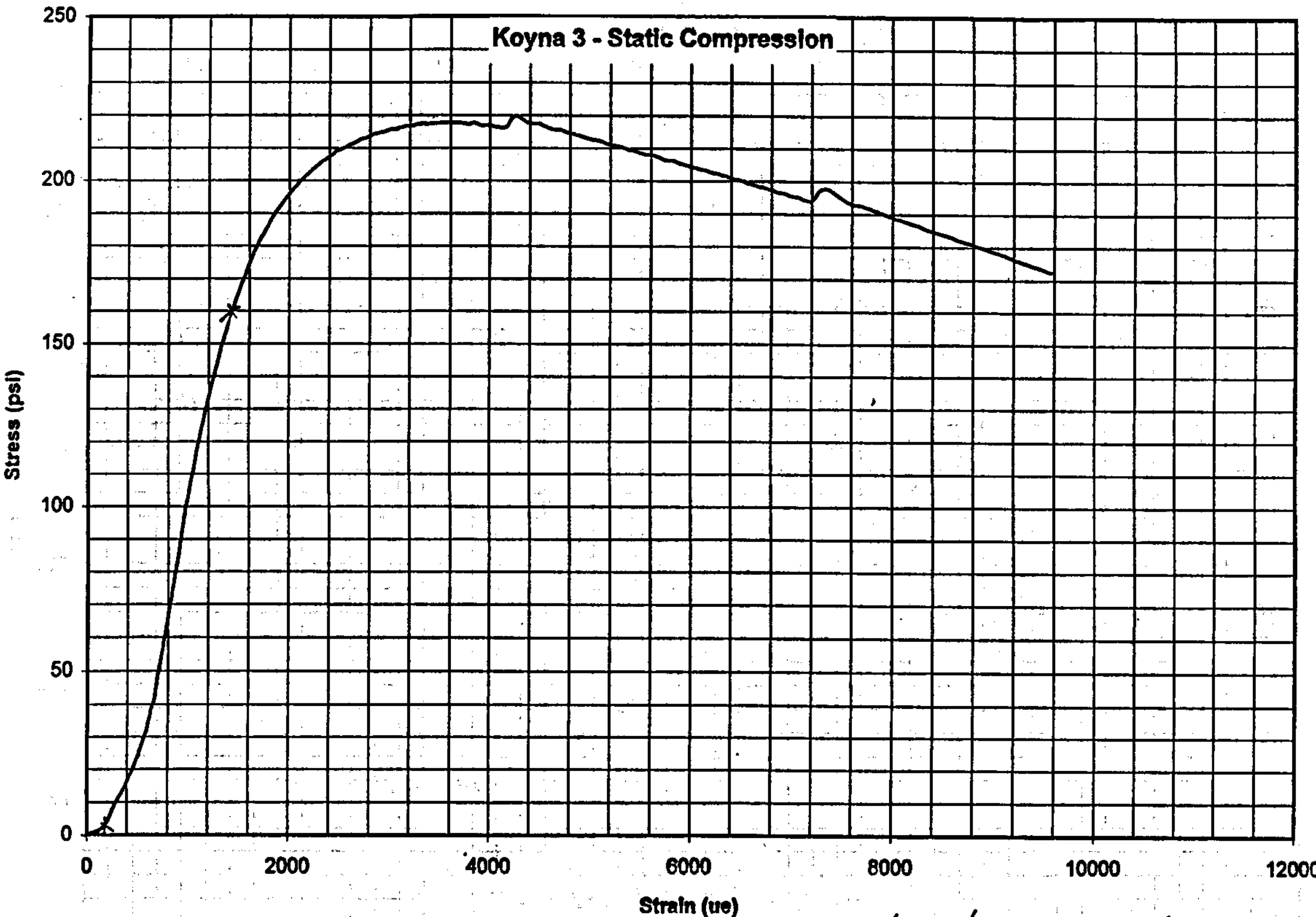


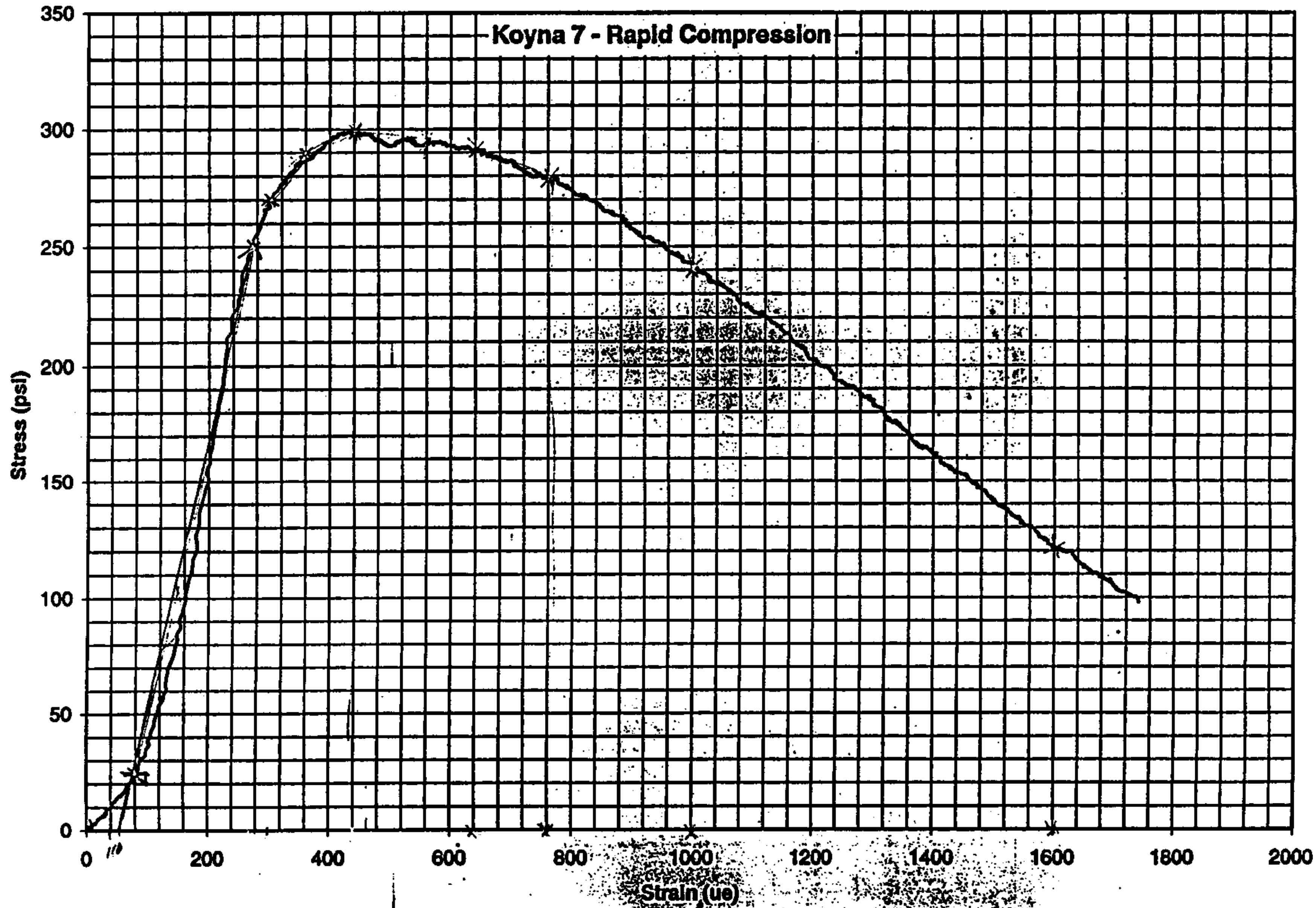
Figure a2

$$\frac{160-14}{1350-400} = .15$$



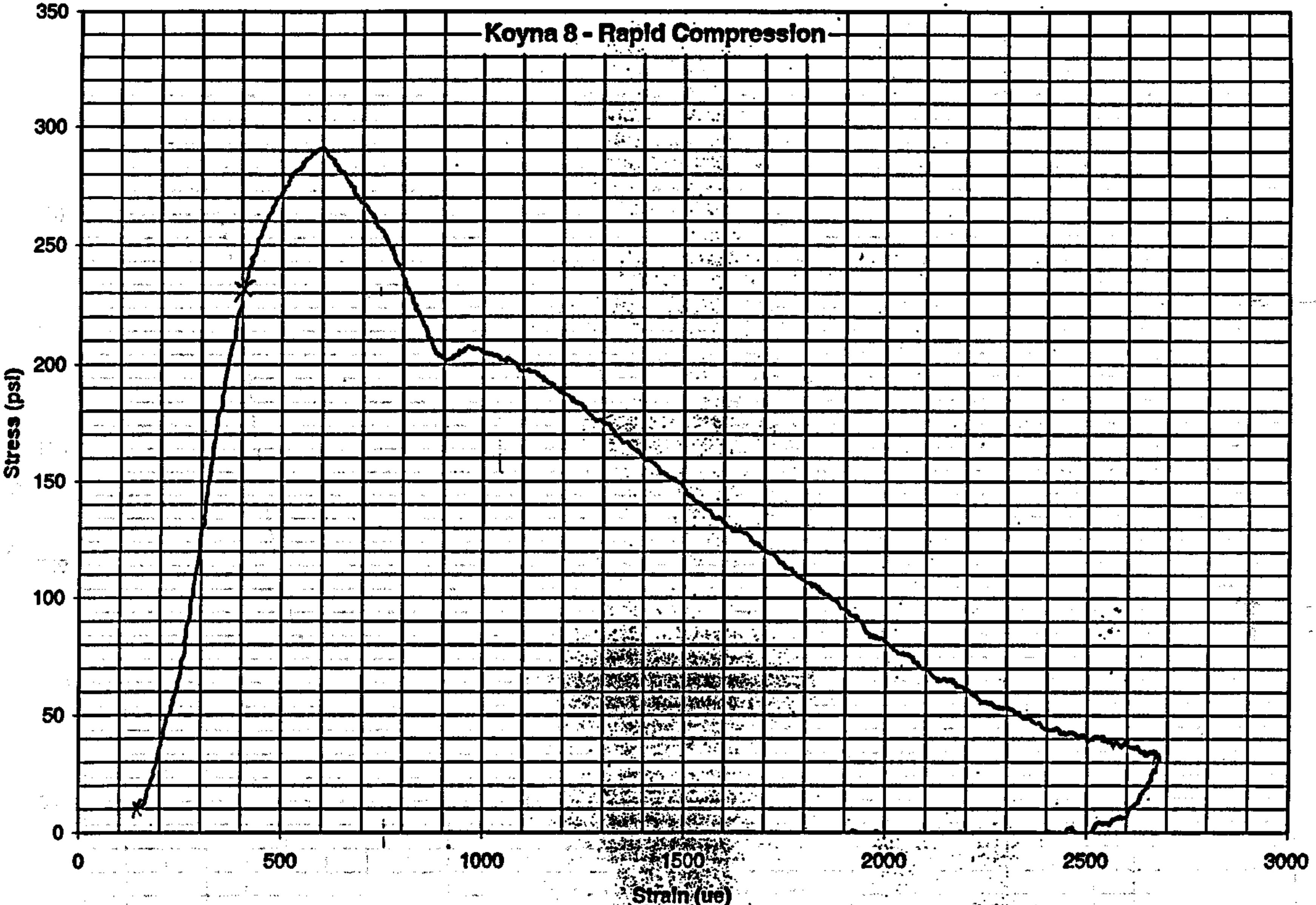
$$\frac{160 - 4}{1350 - 175} = .13 \times 10^6$$

Figure a3



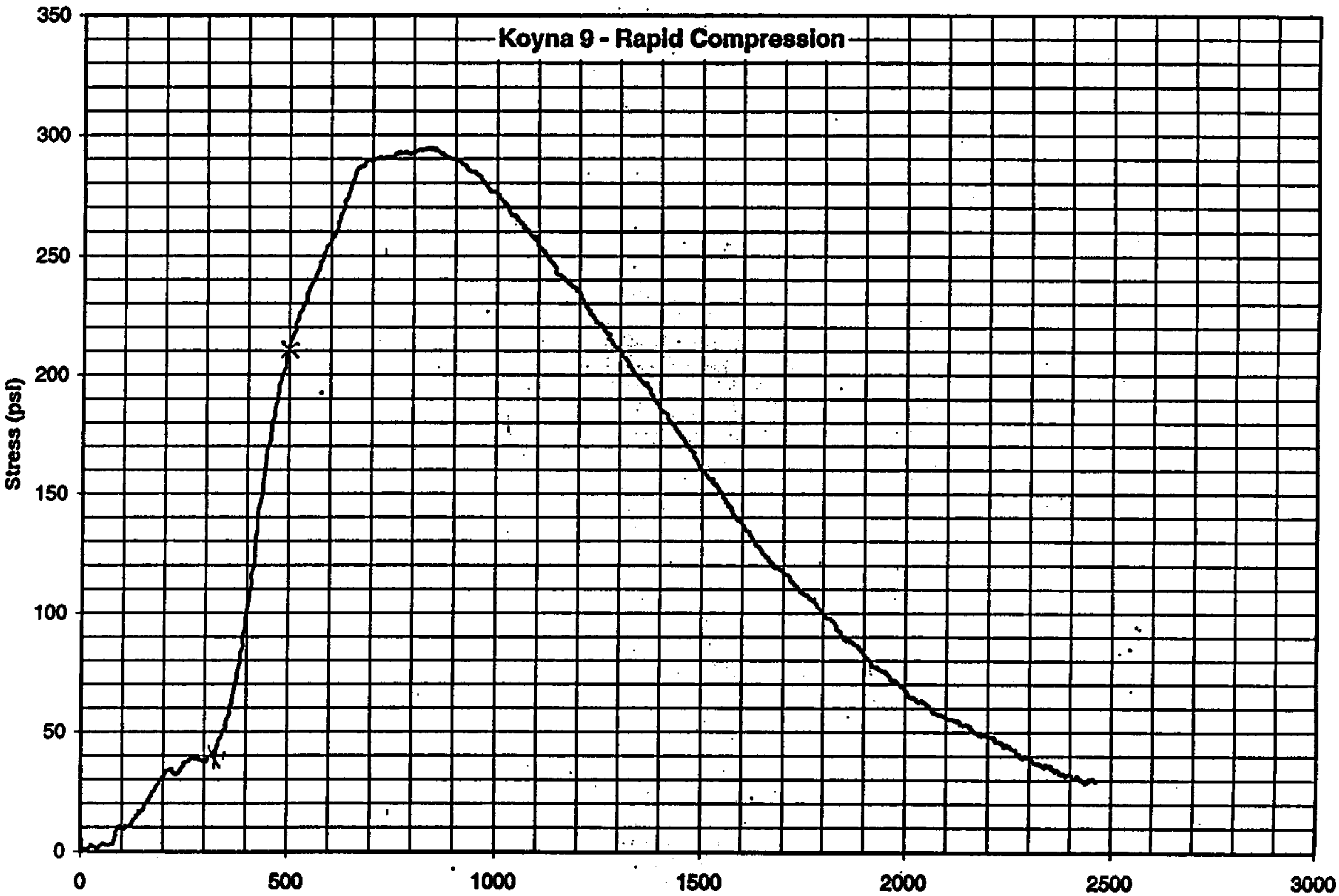
$$\frac{250 - 25}{270 - 80} = .012 \times 10^{6}$$

Figure a4



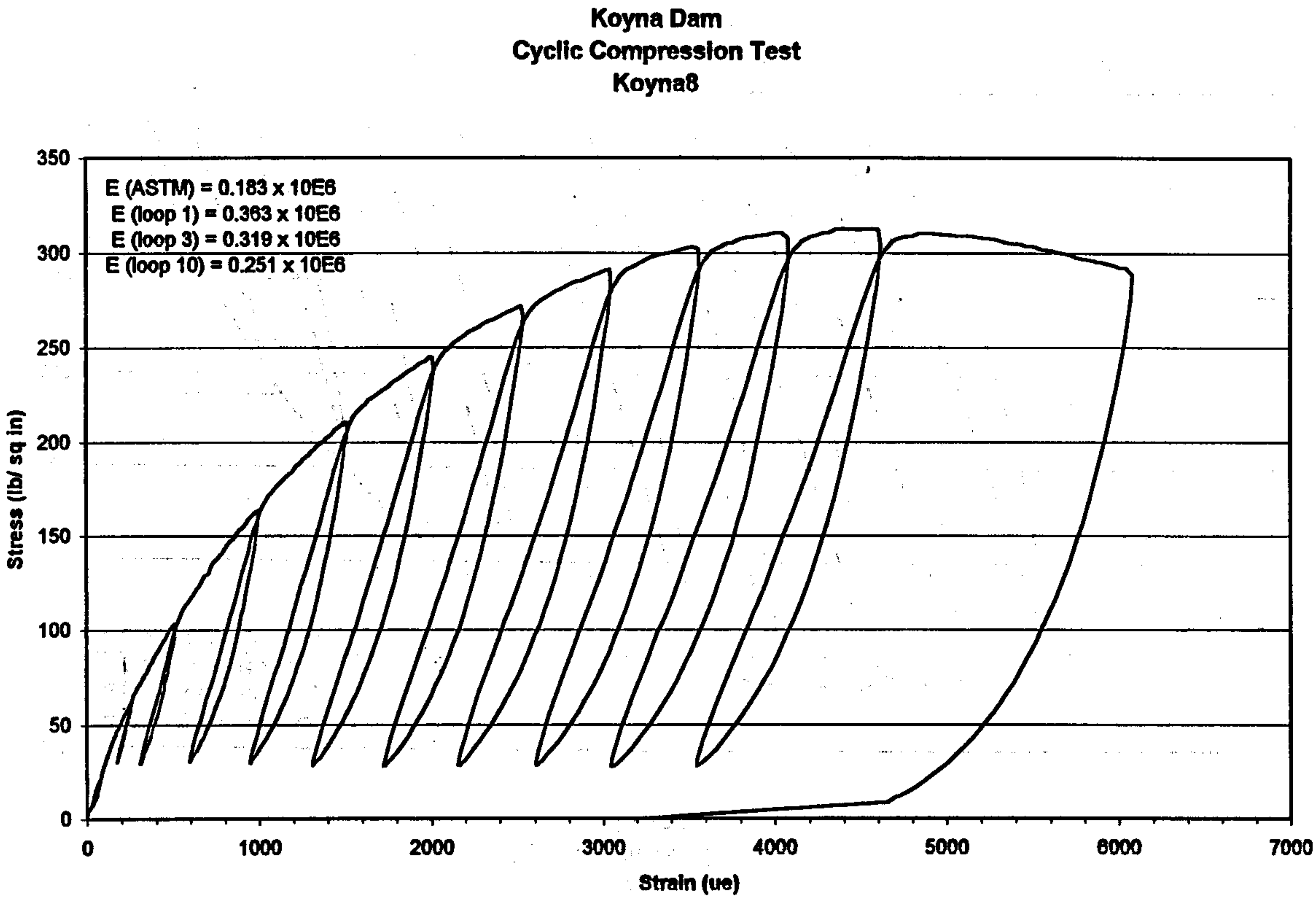
$\frac{410 - 140}{230 - 10} \Rightarrow .012 \times 10^6$

Figure a5



$\dfrac{\dfrac{210 - 40}{500 - 325}}{2} = .97 \times 10^6$

Figure a6.



Koyna Dam
Cyclic Compression Test
Koyna8
E (ASTM) = 0.183 x 10E6
E (loop 1) = 0.363 x 10E6
E (loop 3) = 0.319 x 10E6
E (loop 10) = 0.251 x 10E6
Stress (lb/ sq in)
0
50
100
150
200
250
300
350
Strain (ue)
0
1000
2000
3000
4000
5000
6000
7000

Figure a7

Koyna Dam
Cyclic Compression Test
Koyna9

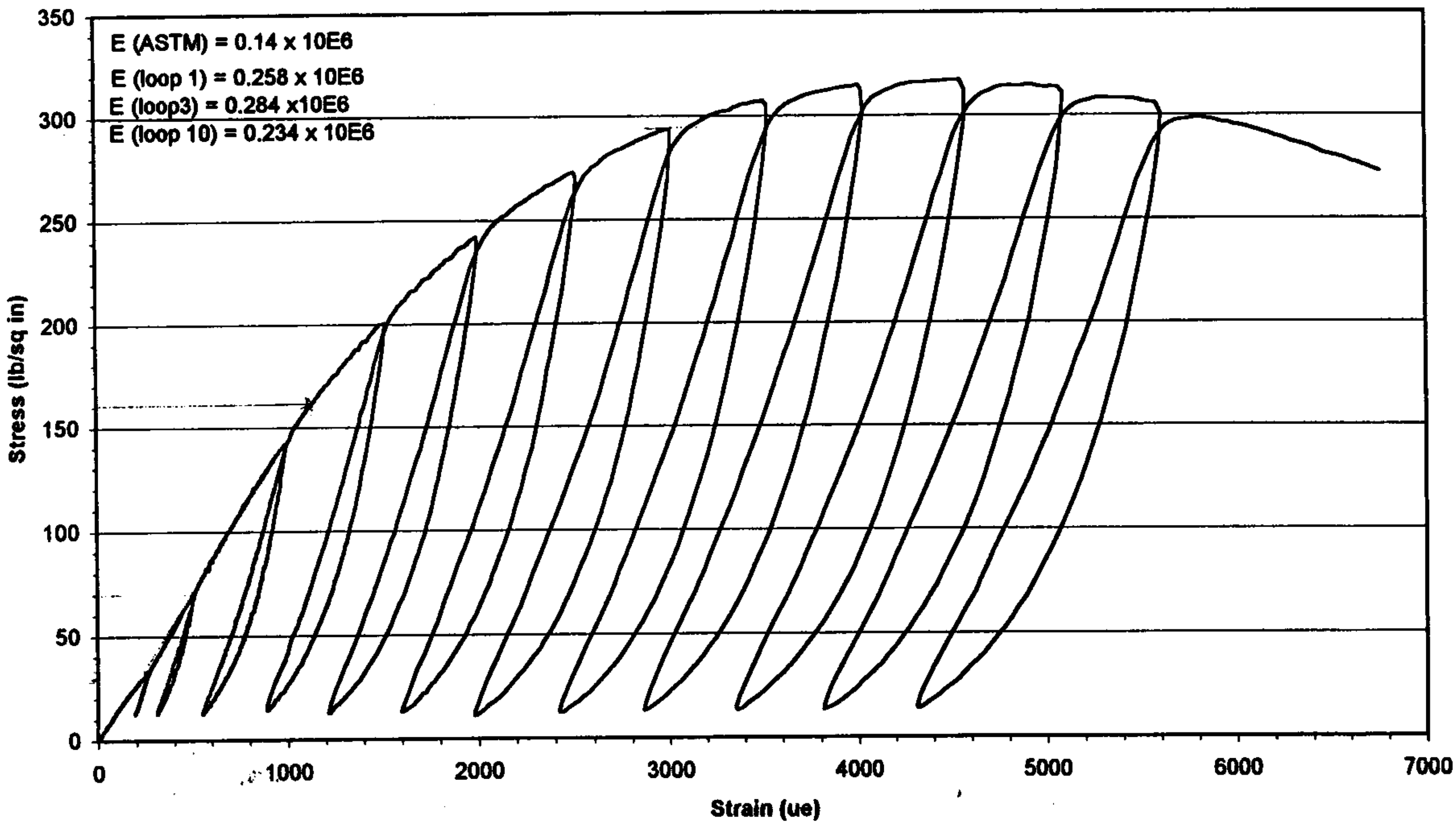
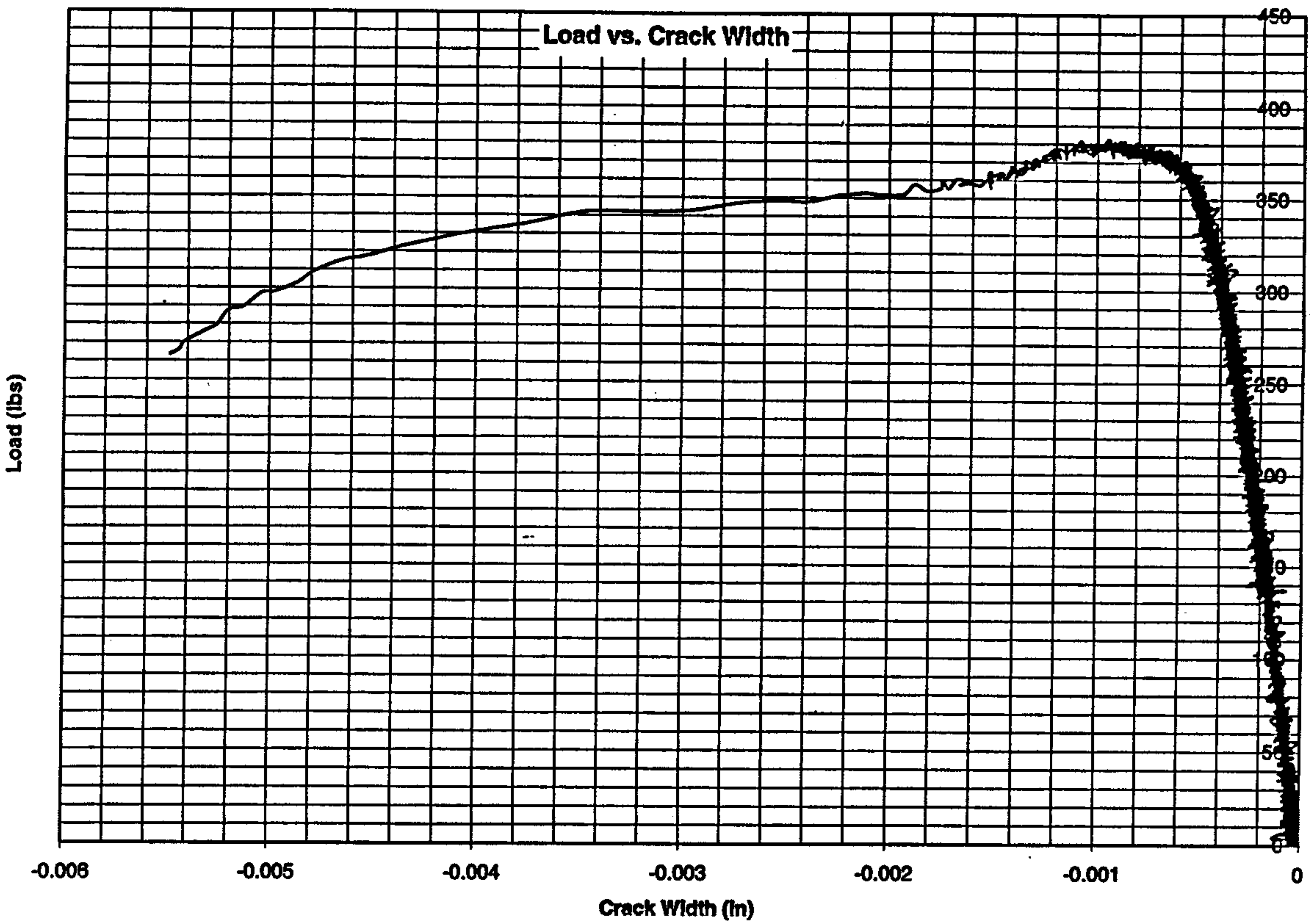


Figure a8



Load vs. Crack Width
Load (lbs)
450
400
350
300
250
Crack Width (in)
-0.006
-0.005
-0.004
-0.003
-0.002
-0.001
0

Figure a9

Appendex B -Laboratory Test Set-Up

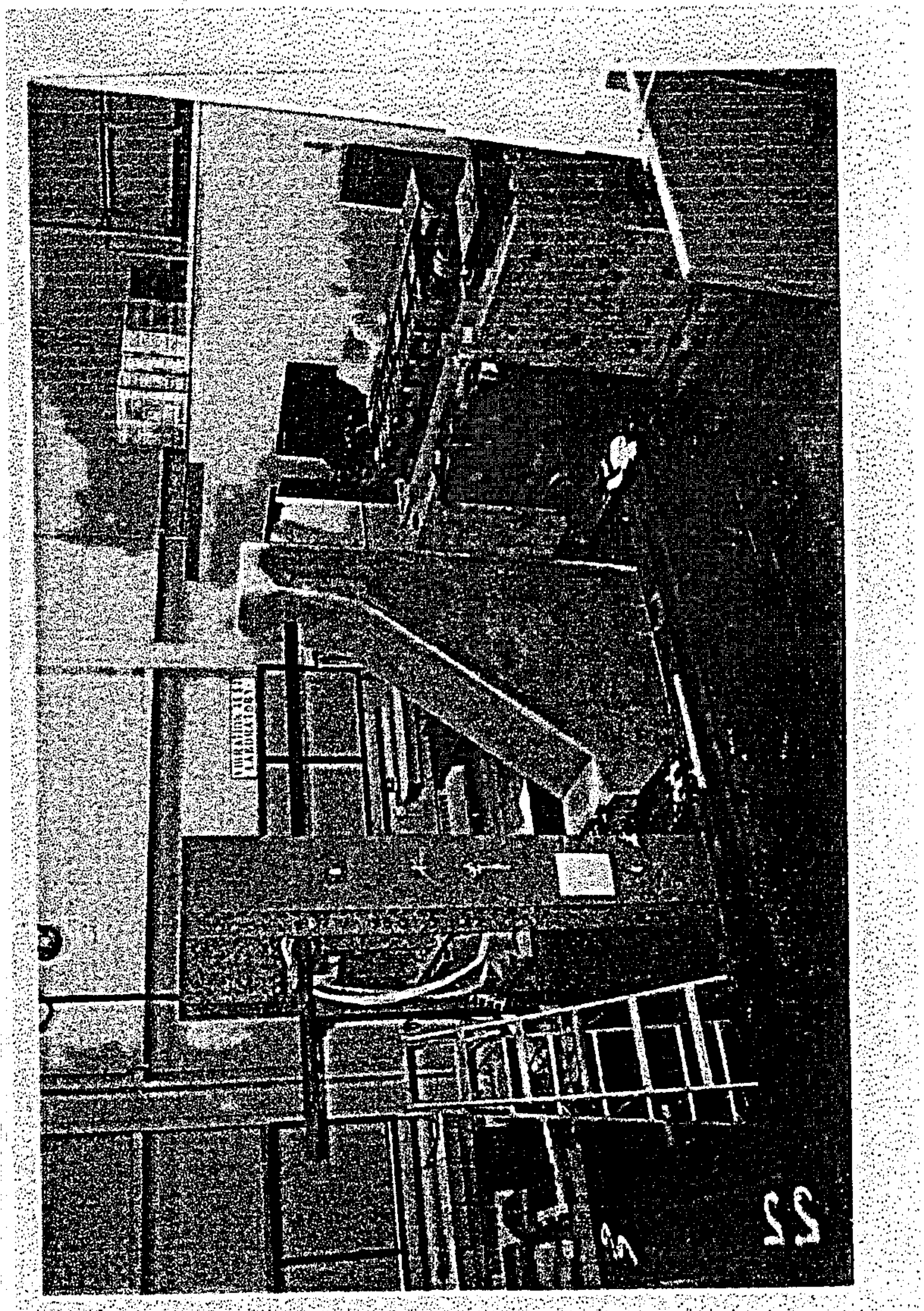


Figure b1

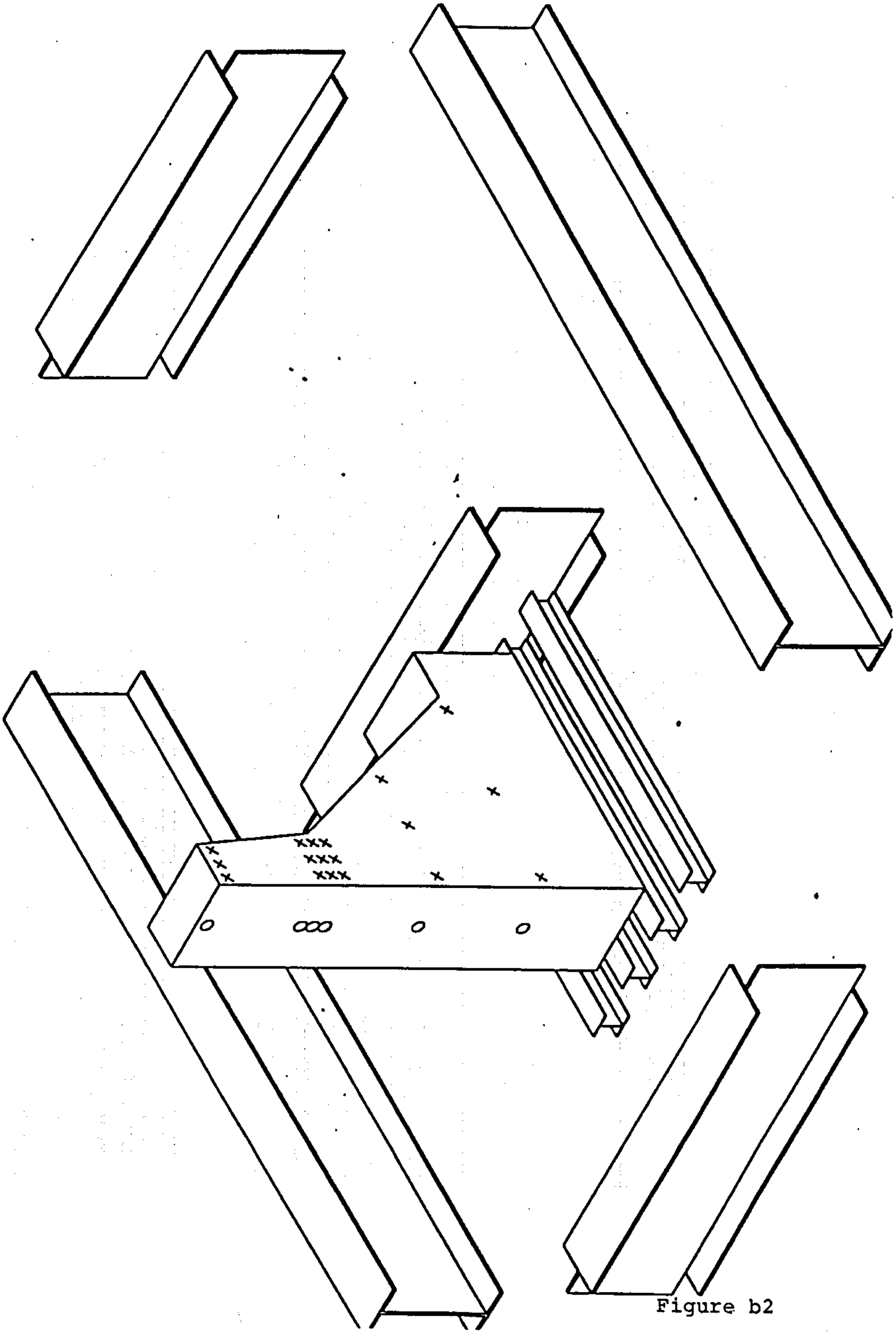


Figure b2

Koyna "Uncracked" Laboratory Model Geometry

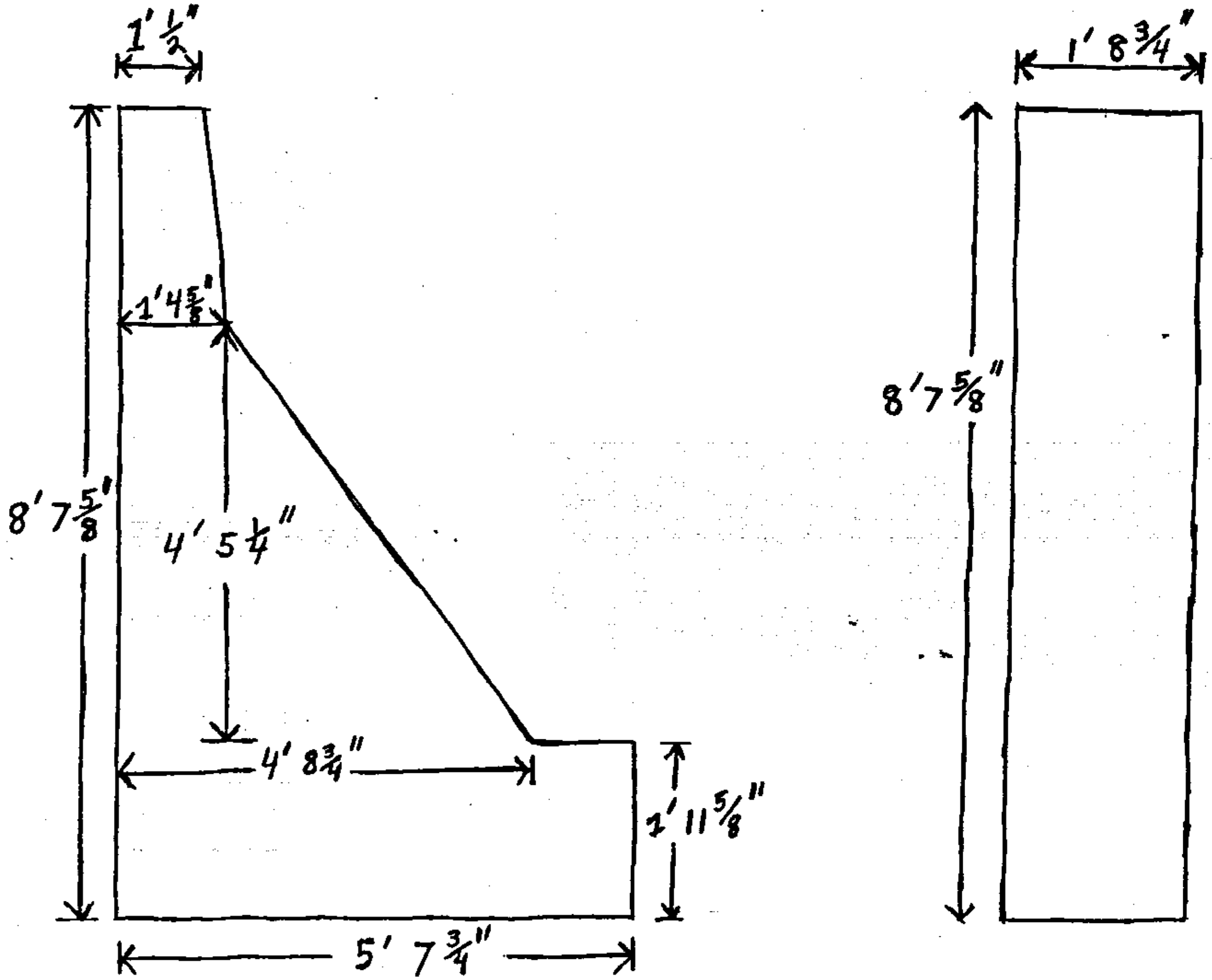


Figure b3

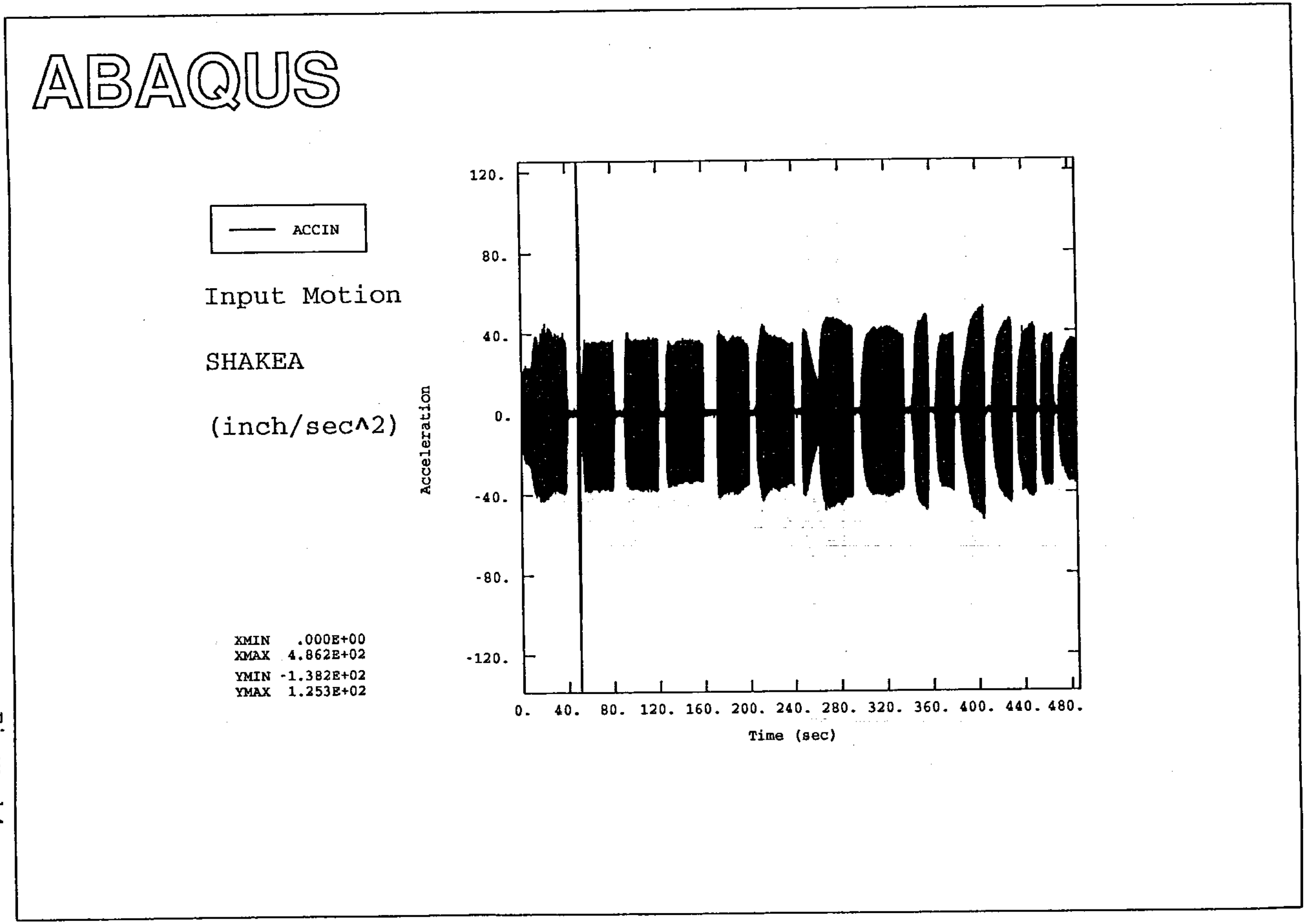

ABAQUS
ACCIN
Input Motion
SHAKEA
(inch/sec^2)
XMIN .000E+00
XMAX 4.862E+02
YMIN -1.382E+02
YMAX 1.253E+02
Acceleration
120.
80.
40.
0.
-40.
-80.
-120.
0. 40. 80. 120. 160. 200. 240. 280. 320. 360. 400. 440. 480.
Time (sec)

Figure b4

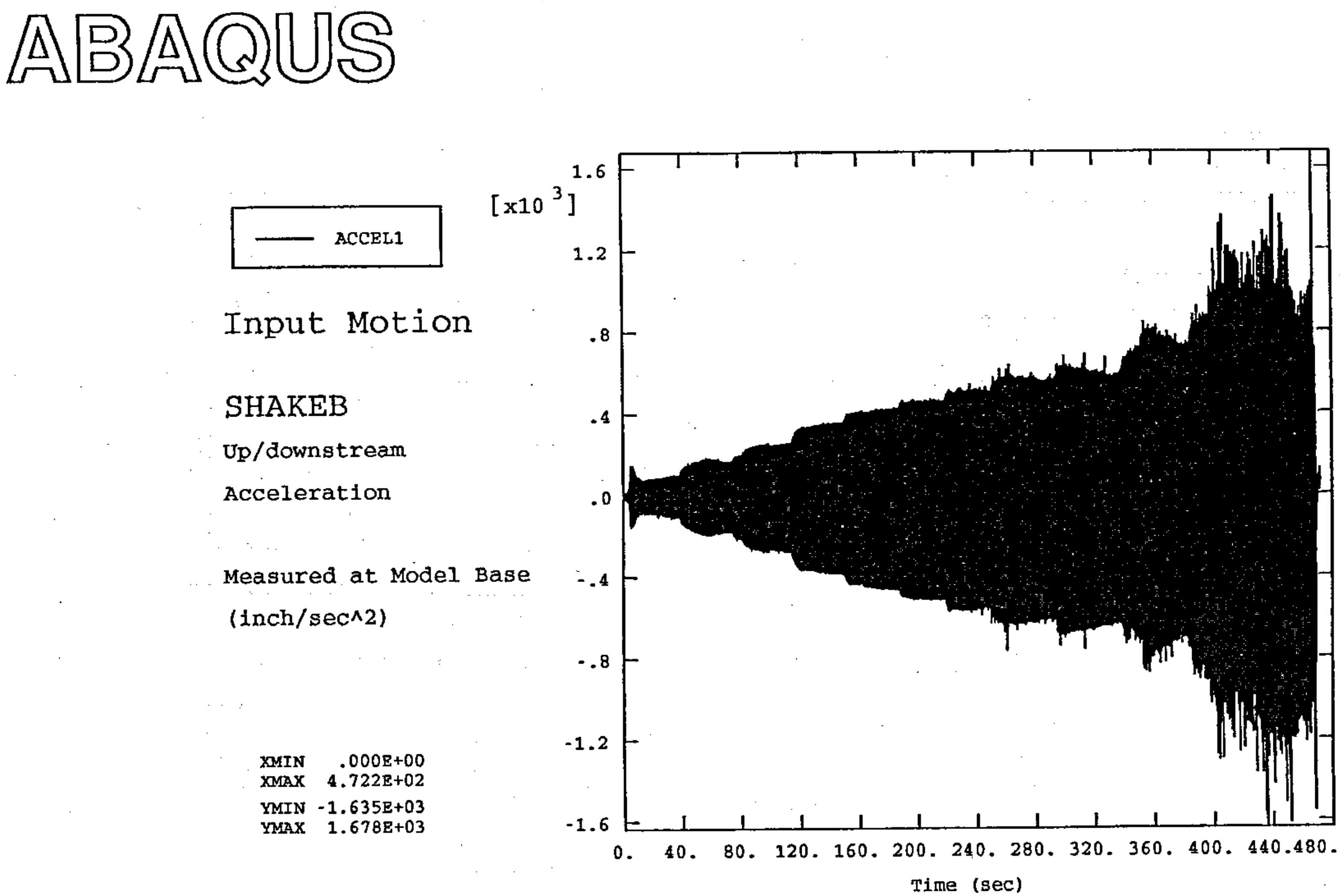
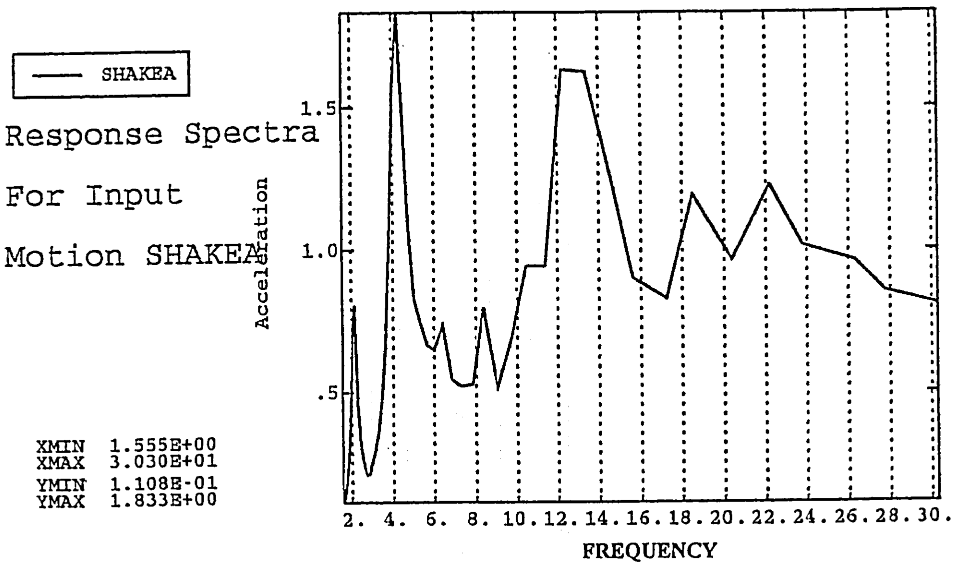

ABAQUS
ACCEL1
Input Motion
SHAKEB
Up/downstream
Acceleration
Measured at Model Base
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.635E+03
YMAX 1.678E+03
[x10 3]
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
0. 40. 80. 120. 160. 200. 240. 280. 320. 360. 400. 440. 480.
Time (sec)

Figure b5

ABAQUS



ABAQUS

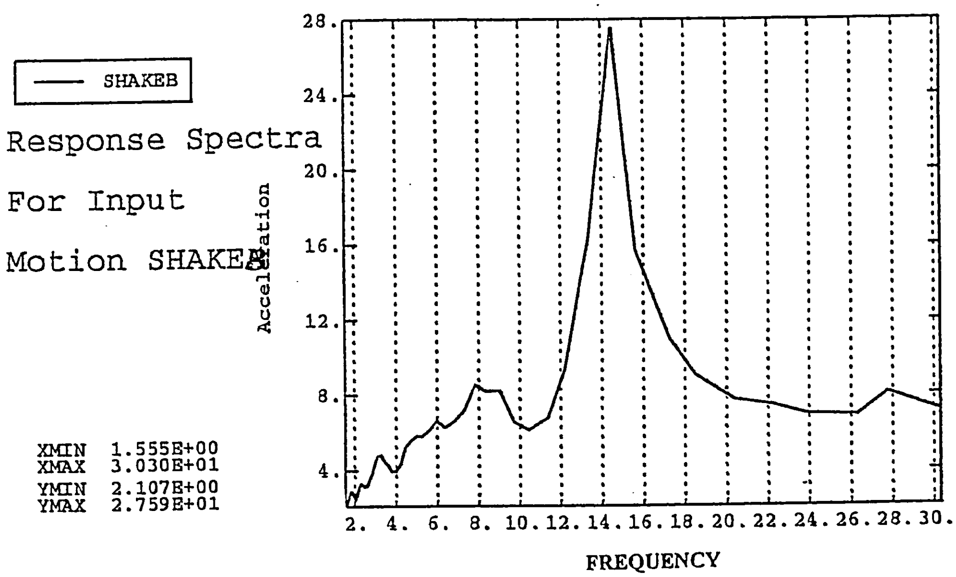


Figure b6

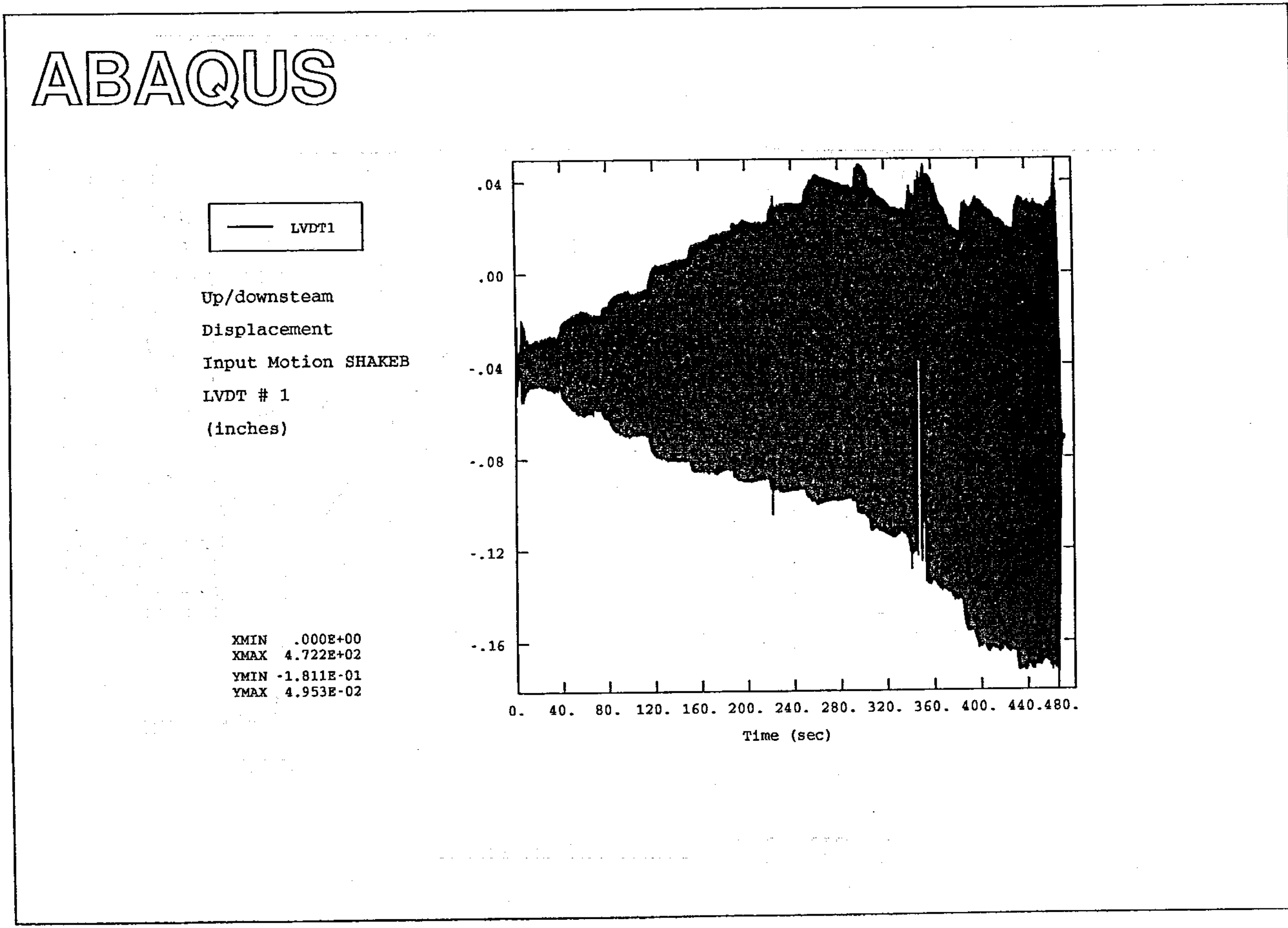
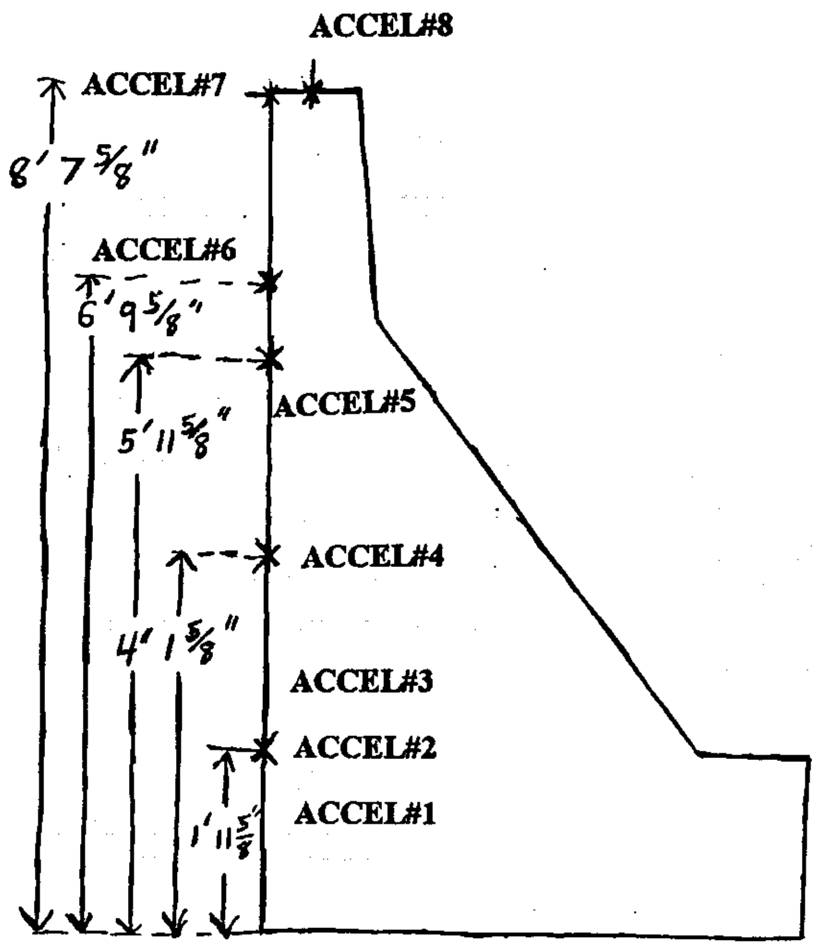
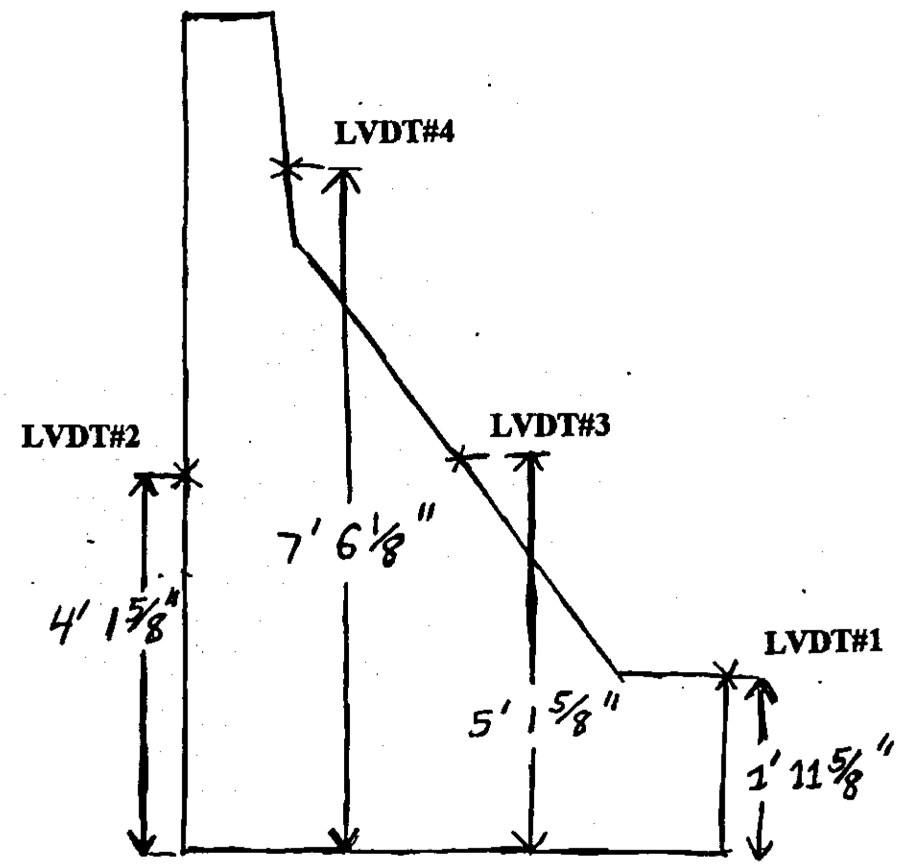

ABAQUS
LVDT1
Up/downsteam
Displacement
Input Motion SHAKEB
LVDT # 1
(inches)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.811E-01
YMAX 4.953E-02
.04
.00
-.04
-.08
-.12
-.16
0. 40. 80. 120. 160. 200. 240. 280. 320. 360. 400. 440. 480.
Time (sec)

Figure b7

INSTRUMENTATION LOCATIONS



ACCELEROMETERS #1 - #8



LVDT'S #1 - #4

Figure b8

Appendix C
Laboratory Shake Test Results

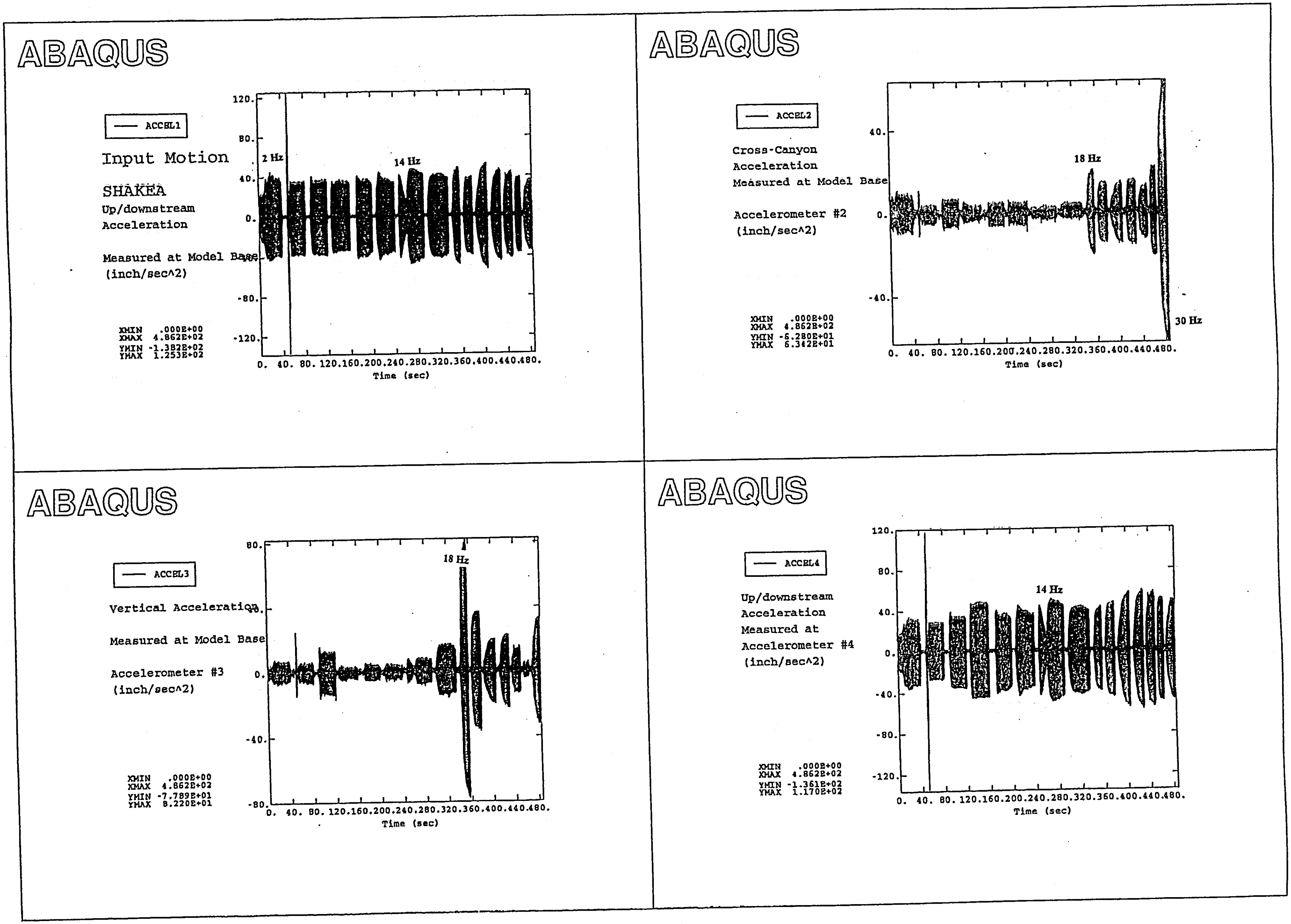

ABAQUS
ACCEL1
Input Motion
SHAKEA
Up/downstream
Acceleration
Measured at Model Base
(inch/sec^2)
2 Hz
14 Hz
XMIN .000E+00
XMAX 4.862E+02
YMIN -1.382E+02
YMAX 1.253E+02
Time (sec)
ABAQUS
ACCEL2
Cross-Canyon
Acceleration
Measured at Model Base
Accelerometer #2
(inch/sec^2)
18 Hz
30 Hz
XMIN .000E+00
XMAX 4.862E+02
YMIN -6.280E+01
YMAX 6.342E+01
Time (sec)
ABAQUS
ACCEL3
Vertical Acceleration
Measured at Model Base
Accelerometer #3
(inch/sec^2)
18 Hz
XMIN .000E+00
XMAX 4.862E+02
YMIN -7.789E+01
YMAX 8.220E+01
Time (sec)
ABAQUS
ACCEL4
Up/downstream
Acceleration
Measured at
Accelerometer #4
(inch/sec^2)
14 Hz
XMIN .000E+00
XMAX 4.862E+02
YMIN -1.361E+02
YMAX 1.170E+02
Time (sec)

Figure C1

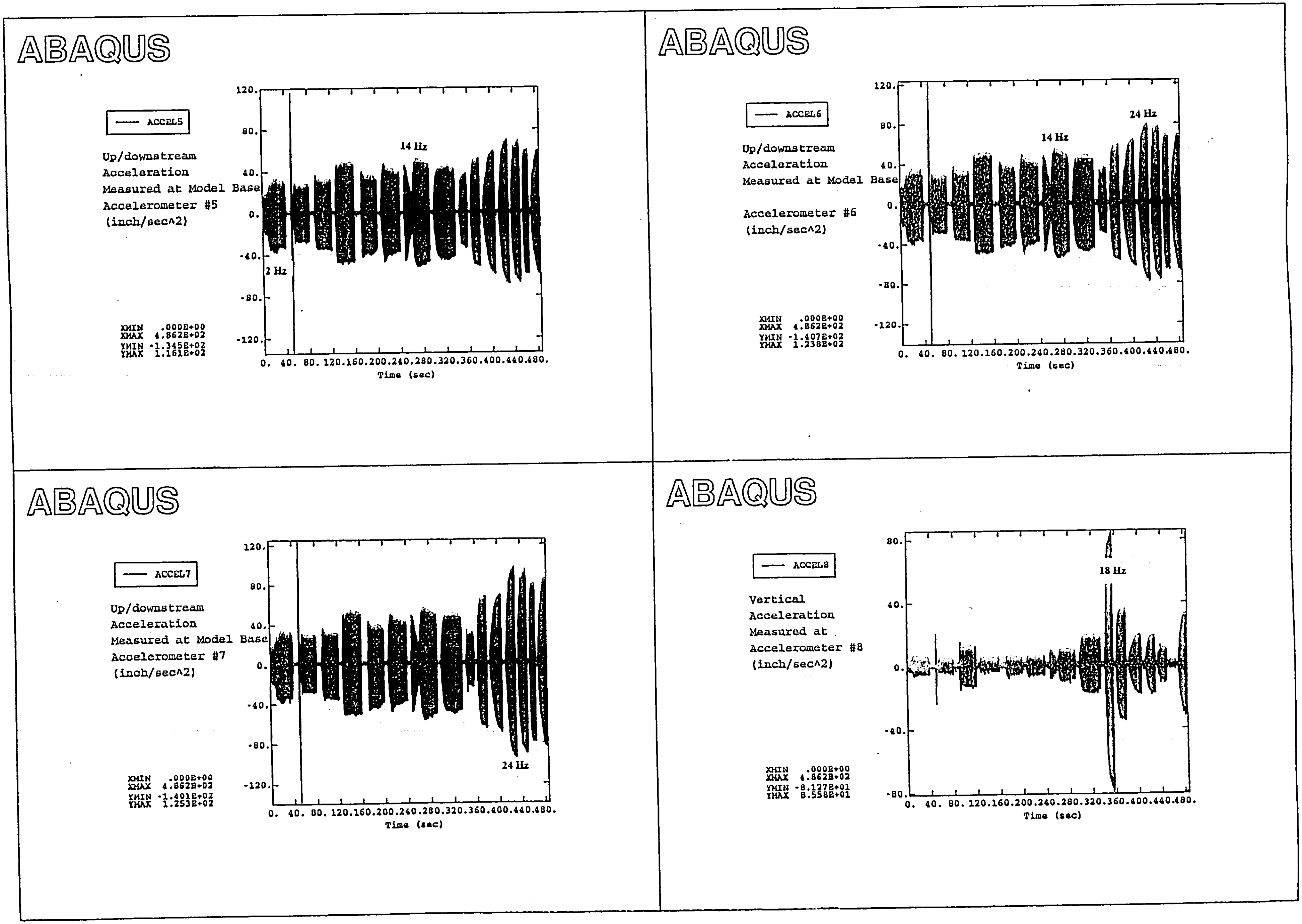

ABAQUS
ACCEL5
Up/downstream
Acceleration
Measured at Model Base
Accelerometer #5
(inch/sec^2)
2 Hz
14 Hz
XMIN .000E+00
XMAX 4.862E+02
YMIN -1.345E+02
YMAX 1.161E+02
Time (sec)
ABAQUS
ACCEL6
Up/downstream
Acceleration
Measured at Model Base
Accelerometer #6
(inch/sec^2)
14 Hz
24 Hz
XMIN .000E+00
XMAX 4.862E+02
YMIN -1.407E+02
YMAX 1.238E+02
Time (sec)
ABAQUS
ACCEL7
Up/downstream
Acceleration
Measured at Model Base
Accelerometer #7
(inch/sec^2)
24 Hz
XMIN .000E+00
XMAX 4.862E+02
YMIN -1.401E+02
YMAX 1.253E+02
Time (sec)
ABAQUS
ACCEL8
Vertical
Acceleration
Measured at
Accelerometer #8
(inch/sec^2)
18 Hz
XMIN .000E+00
XMAX 4.862E+02
YMIN -8.127E+01
YMAX 8.558E+01
Time (sec)

Figure c2

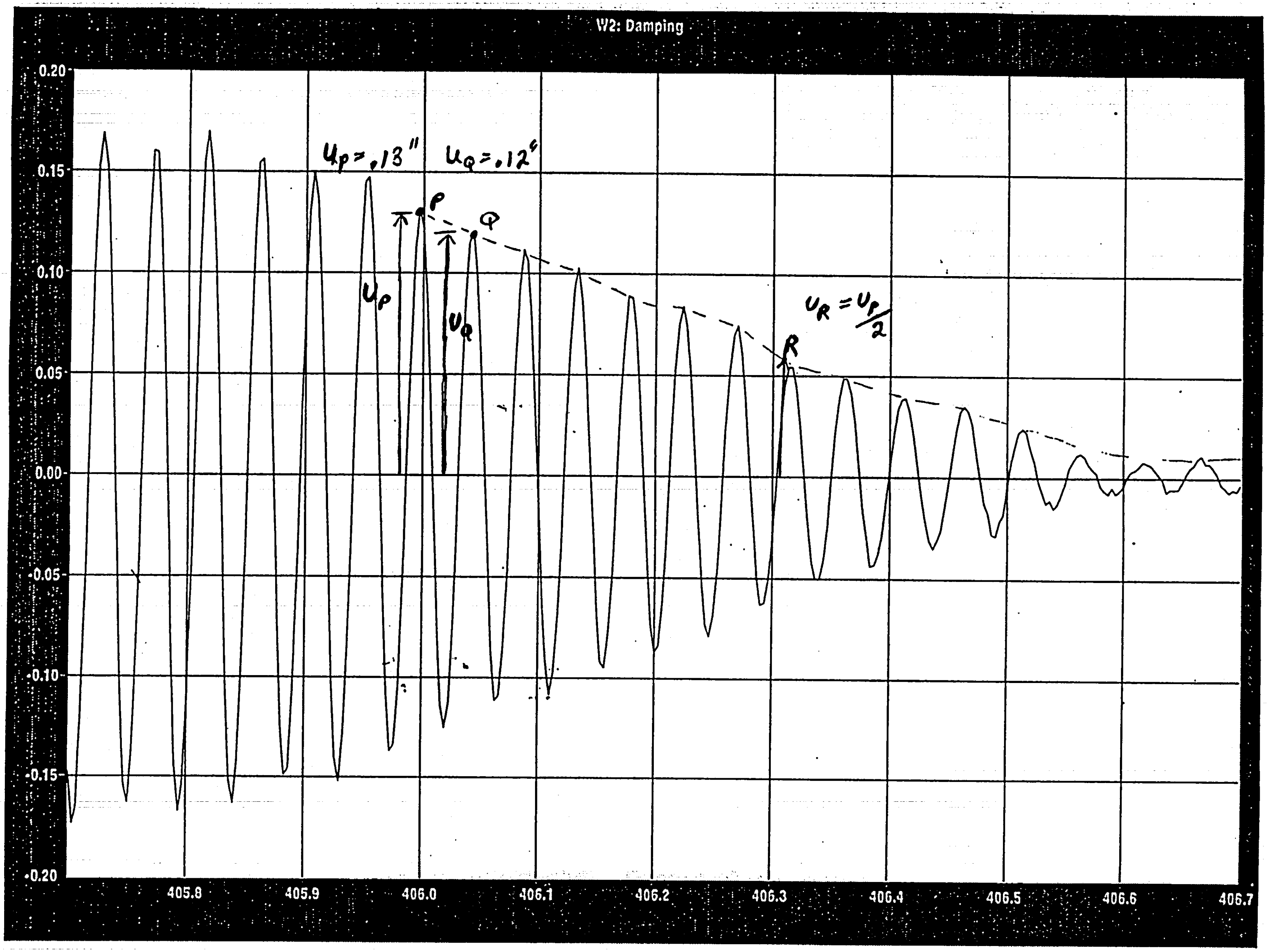

W2: Damping
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
405.8
405.9
406.0
406.1
406.2
406.3
406.4
406.5
406.6
406.7
Up = .13"
UQ = .12"
P
Q
R
Up
UQ
UR = UP/2

Figure c3

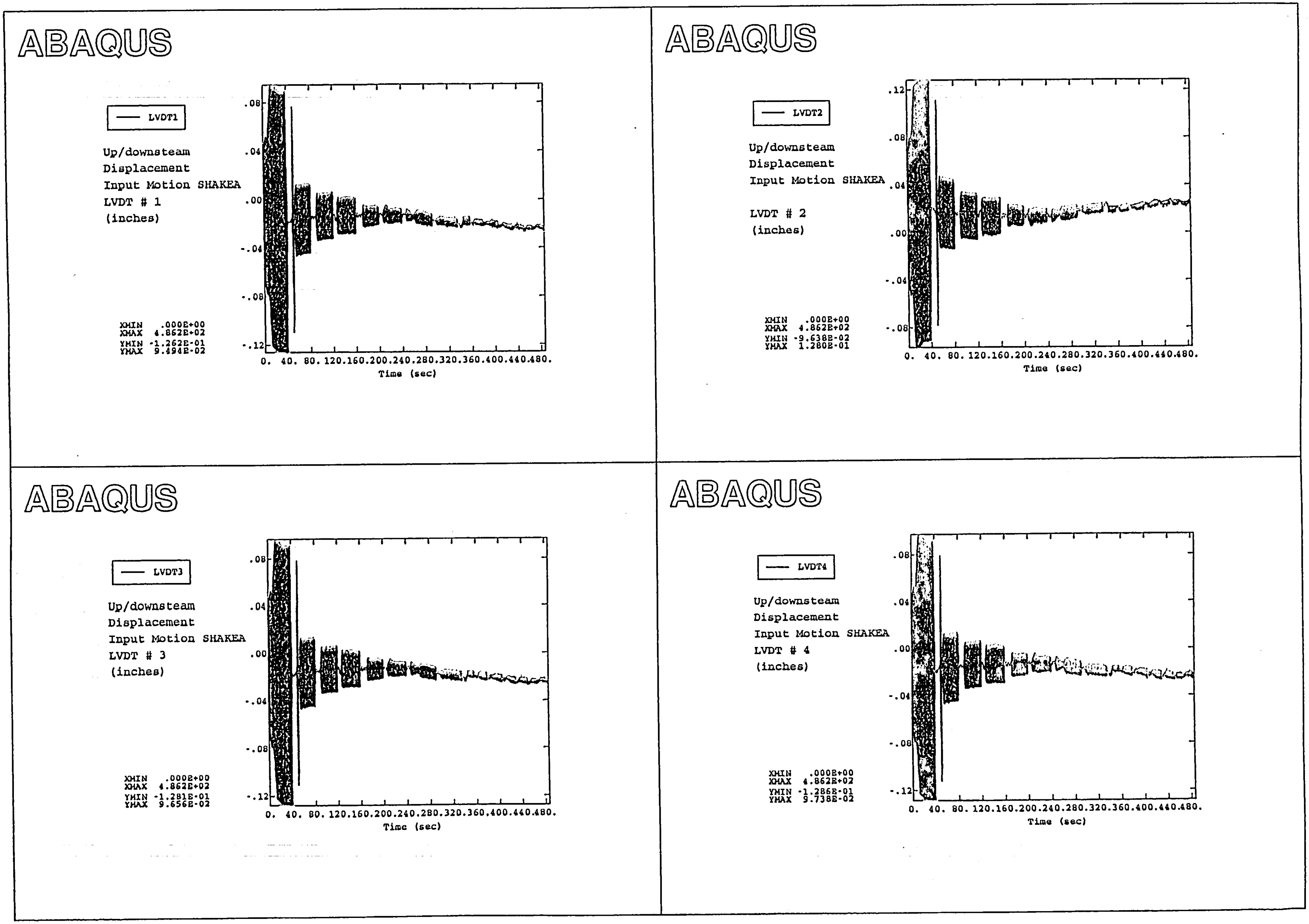
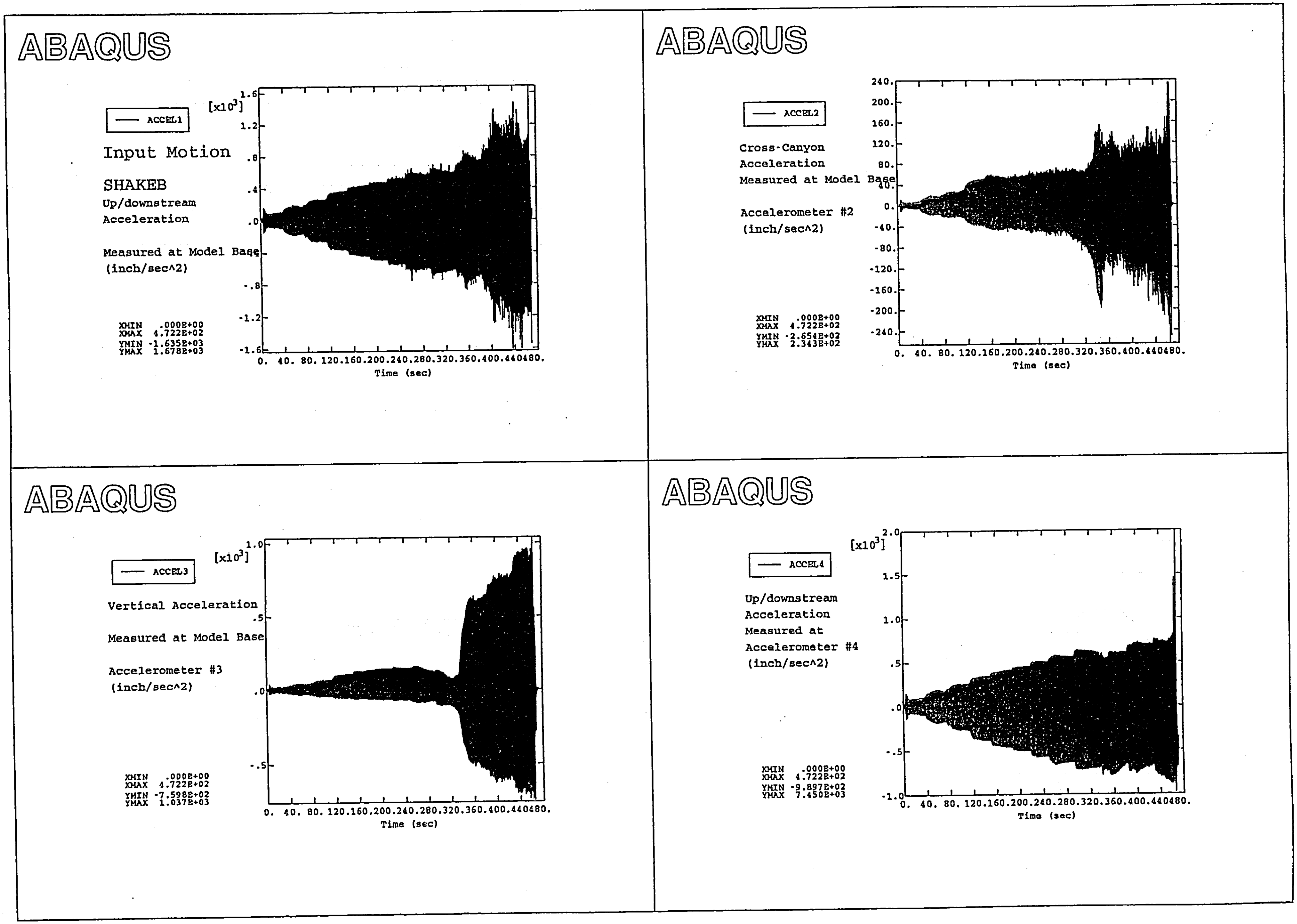

ABAQUS
LVDT1
Up/downsteam
Displacement
Input Motion SHAKEA
LVDT # 1
(inches)
XMIN .000E+00
XMAX 4.862E+02
YMIN -1.262E-01
YMAX 9.494E-02
.08
.04
.00
-.04
-.08
-.12
0. 40. 80. 120. 160. 200. 240. 280. 320. 360. 400. 440. 480.
Time (sec)
ABAQUS
LVDT2
Up/downsteam
Displacement
Input Motion SHAKEA
LVDT # 2
(inches)
XMIN .000E+00
XMAX 4.862E+02
YMIN -9.638E-02
YMAX 1.280E-01
.12
.08
.04
.00
-.04
-.08
0. 40. 80. 120. 160. 200. 240. 280. 320. 360. 400. 440. 480.
Time (sec)
ABAQUS
LVDT3
Up/downsteam
Displacement
Input Motion SHAKEA
LVDT # 3
(inches)
XMIN .000E+00
XMAX 4.862E+02
YMIN -1.281E-01
YMAX 9.656E-02
.08
.04
.00
-.04
-.08
-.12
0. 40. 80. 120. 160. 200. 240. 280. 320. 360. 400. 440. 480.
Time (sec)
ABAQUS
LVDT4
Up/downsteam
Displacement
Input Motion SHAKEA
LVDT # 4
(inches)
XMIN .000E+00
XMAX 4.862E+02
YMIN -1.286E-01
YMAX 9.738E-02
.08
.04
.00
-.04
-.08
-.12
0. 40. 80. 120. 160. 200. 240. 280. 320. 360. 400. 440. 480.
Time (sec)

Figure C4



ABAQUS
ACCEL1
Input Motion
SHAKEB
Up/downstream
Acceleration
Measured at Model Base
(inch/sec^2)
[x10^3]
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.635E+03
YMAX 1.678E+03
Time (sec)
ABAQUS
ACCEL2
Cross-Canyon
Acceleration
Measured at Model Base
Accelerometer #2
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -2.654E+02
YMAX 2.343E+02
Time (sec)
ABAQUS
ACCEL3
Vertical Acceleration
Measured at Model Base
Accelerometer #3
(inch/sec^2)
[x10^3]
XMIN .000E+00
XMAX 4.722E+02
YMIN -7.598E+02
YMAX 1.037E+03
Time (sec)
ABAQUS
ACCEL4
Up/downstream
Acceleration
Measured at
Accelerometer #4
(inch/sec^2)
[x10^3]
XMIN .000E+00
XMAX 4.722E+02
YMIN -9.897E+02
YMAX 7.450E+03
Time (sec)

Figure C5

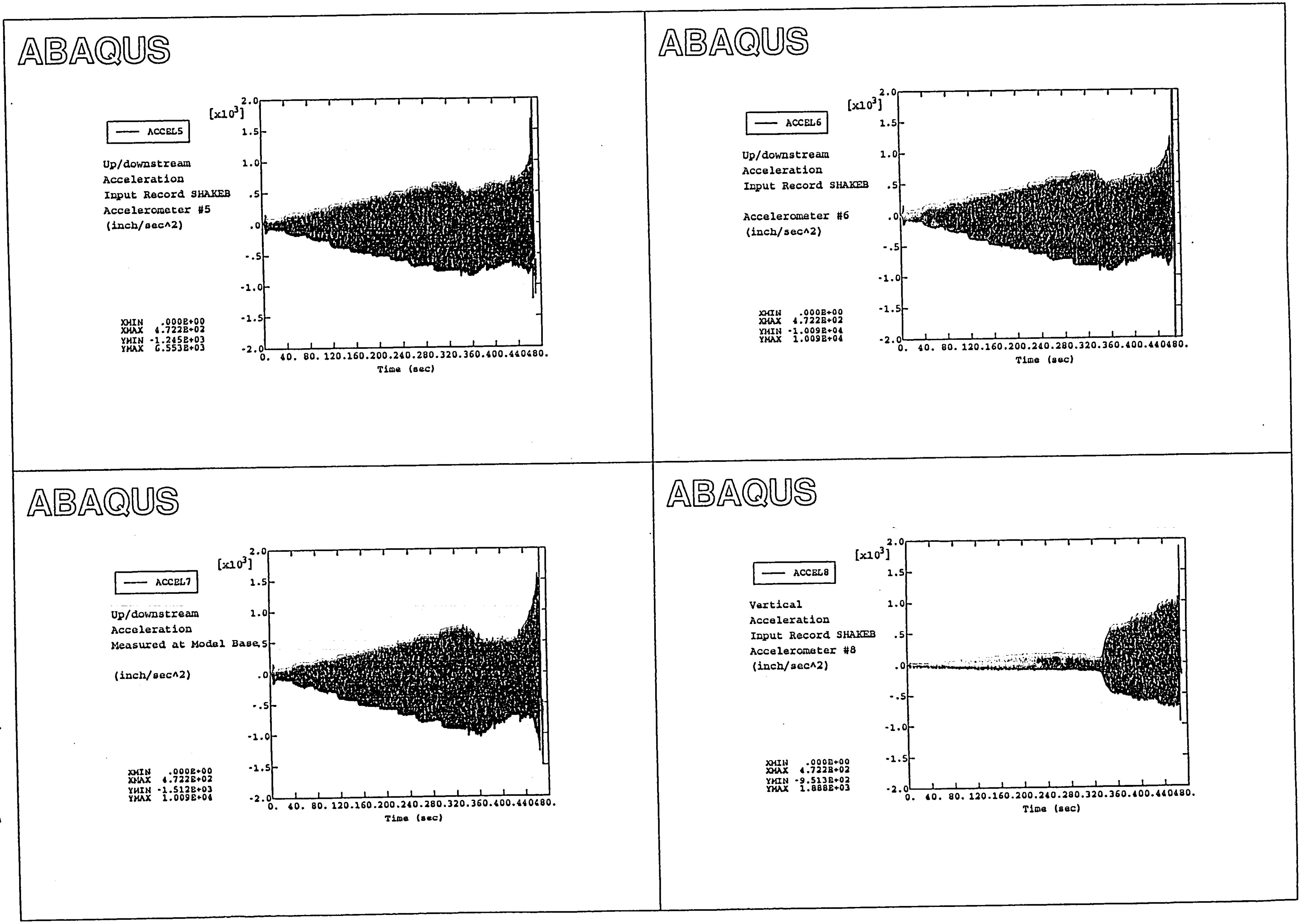

ABAQUS
ACCEL5
Up/downstream
Acceleration
Input Record SHAKEB
Accelerometer #5
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.245E+03
YMAX 6.553E+03
[x10^3]
2.0
1.5
1.0
.5
.0
-.5
-1.0
-1.5
-2.0
0. 40. 80. 120. 160. 200. 240. 280. 320. 360. 400. 440 480.
Time (sec)
ABAQUS
ACCEL6
Up/downstream
Acceleration
Input Record SHAKEB
Accelerometer #6
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.009E+04
YMAX 1.009E+04
ABAQUS
ACCEL7
Up/downstream
Acceleration
Measured at Model Base
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.512E+03
YMAX 1.009E+04
ABAQUS
ACCEL8
Vertical
Acceleration
Input Record SHAKEB
Accelerometer #8
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -9.513E+02
YMAX 1.888E+03

Figure C6

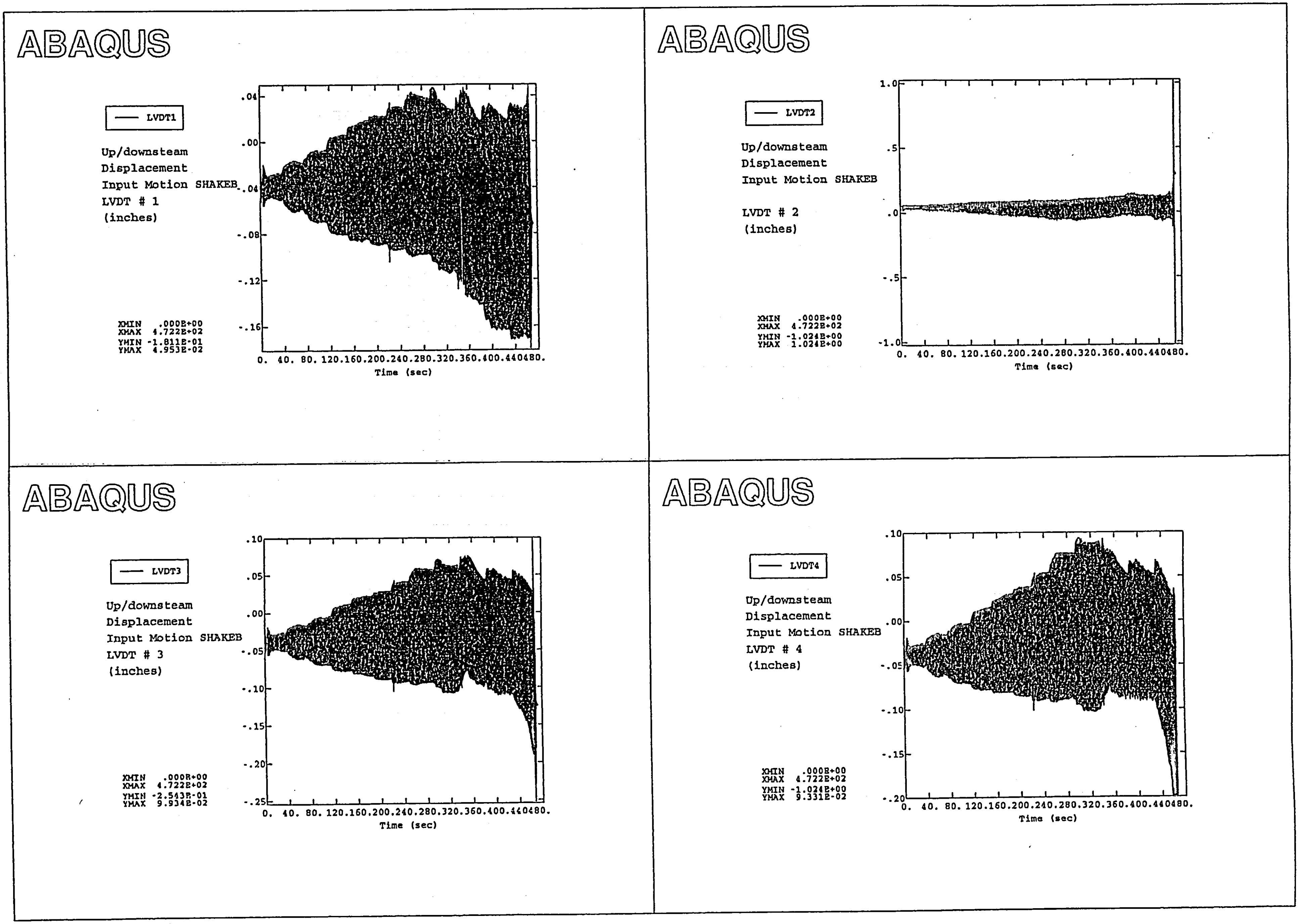

ABAQUS
LVDT1
Up/downsteam
Displacement
Input Motion SHAKEB
LVDT # 1
(inches)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.811E-01
YMAX 4.953E-02
.04
.00
-.04
-.08
-.12
-.16
0. 40. 80. 120.160.200.240.280.320.360.400.440480.
Time (sec)
ABAQUS
LVDT2
Up/downsteam
Displacement
Input Motion SHAKEB
LVDT # 2
(inches)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.024E+00
YMAX 1.024E+00
1.0
.5
.0
-.5
-1.0
0. 40. 80. 120.160.200.240.280.320.360.400.440480.
Time (sec)
ABAQUS
LVDT3
Up/downsteam
Displacement
Input Motion SHAKEB
LVDT # 3
(inches)
XMIN .000E+00
XMAX 4.722E+02
YMIN -2.543E-01
YMAX 9.934E-02
.10
.05
.00
-.05
-.10
-.15
-.20
-.25
0. 40. 80. 120.160.200.240.280.320.360.400.440480.
Time (sec)
ABAQUS
LVDT4
Up/downsteam
Displacement
Input Motion SHAKEB
LVDT # 4
(inches)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.024E+00
YMAX 9.331E-02
.10
.05
.00
-.05
-.10
-.15
-.20
0. 40. 80. 120.160.200.240.280.320.360.400.440480.
Time (sec)

Figure c7

Koyna Laboratory Model Test
Final Cracking Pattern

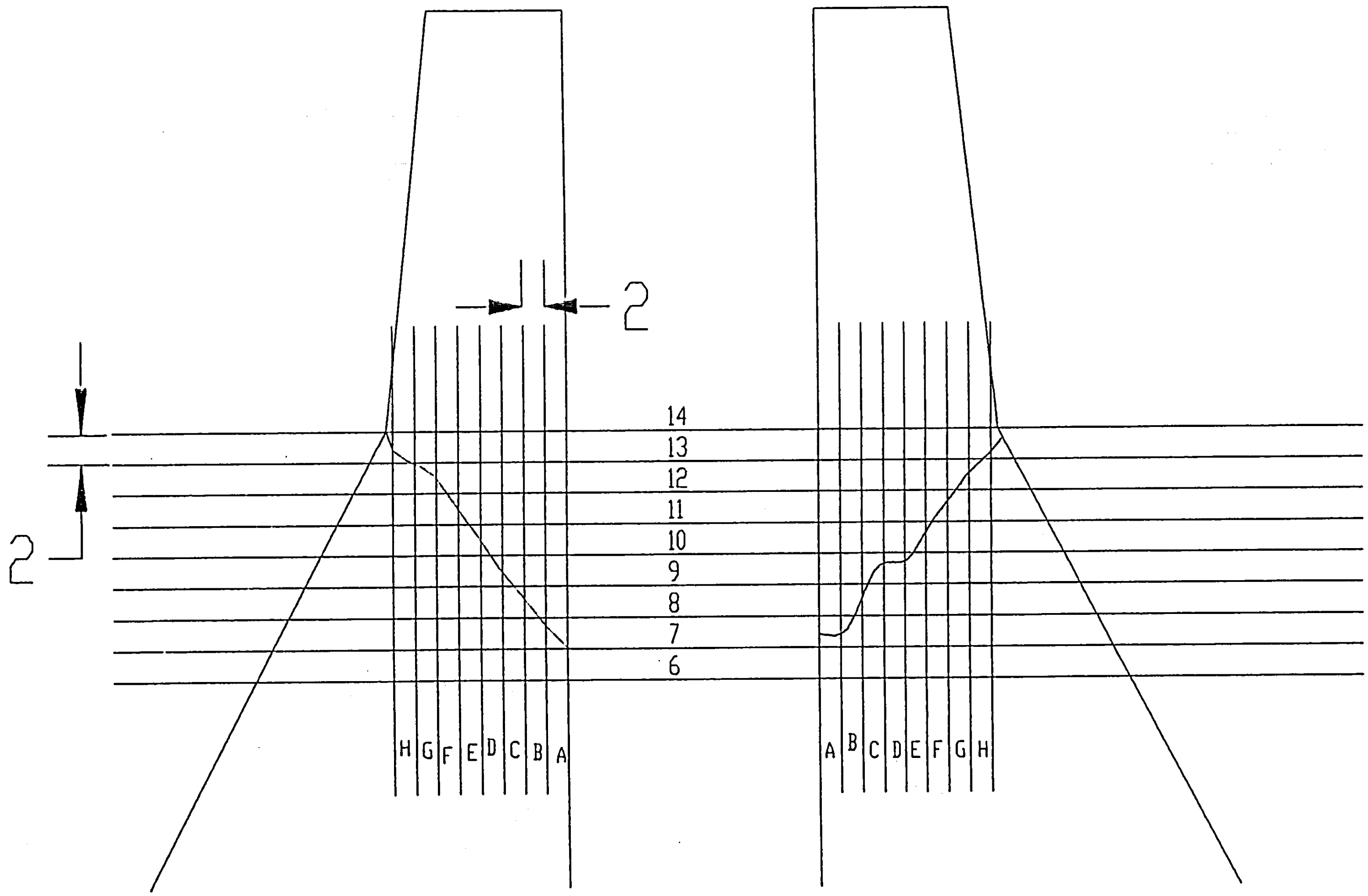


Figure C8

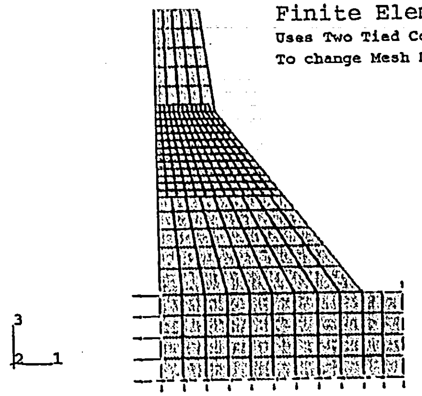
Appendix D
ABAQUS Finite Element Models

ABAQUS

Koyna Laboratory Model Study
Uncracked Model Study
Used to Evaluate
Linear and Non-linear
Material Propertys
For
ABAQUS STANDARD & EXPLICIT

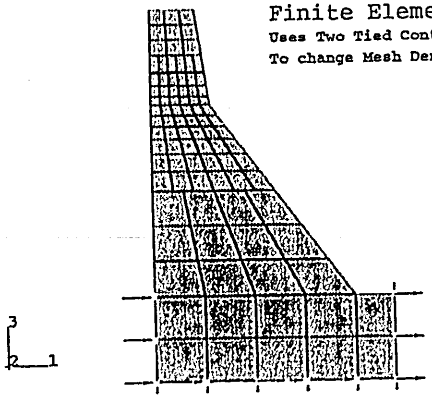
Determination of Mesh Sensitivity
Non-linear Material Propertys
Failure Stress = 55 psi
Mode I Fracture Energy = 0.2012
Crack Opening Strain = .001375

ABAQUS



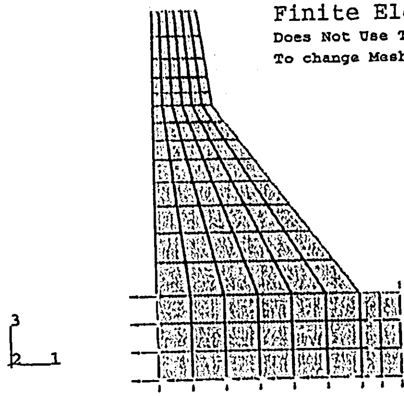
Finite Element Mesh #1
Uses Two Tied Contact Surfaces
To change Mesh Density

ABAQUS



Finite Element Mesh #2
Uses Two Tied Contact Surfaces
To change Mesh Density

ABAQUS



Finite Element Mesh #3
Does Not Use Tied Contact Surfaces
To change Mesh Density

Figure d1

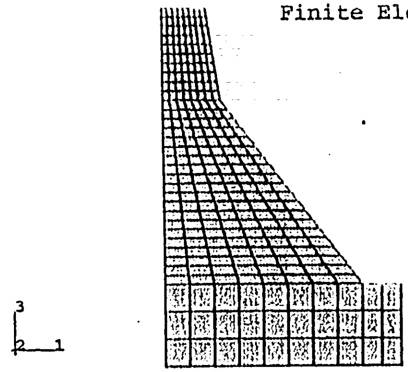
ABAQUS

Koyna Laboratory Model Study
Uncracked Model Study
Used to Evaluate
Linear and Non-linear
Material Propertys
For
ABAQUS STANDARD & EXPLICIT

Determination of Mesh Sensitivity

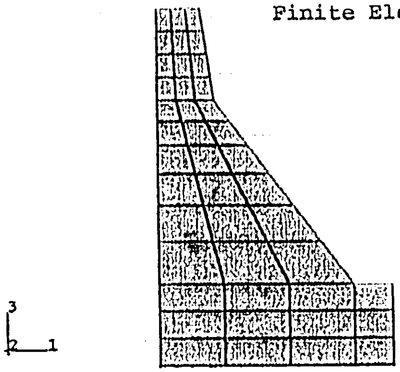
ABAQUS

Finite Element Mesh #4



ABAQUS

Finite Element Mesh #5



ABAQUS

Finite Element Mesh #6

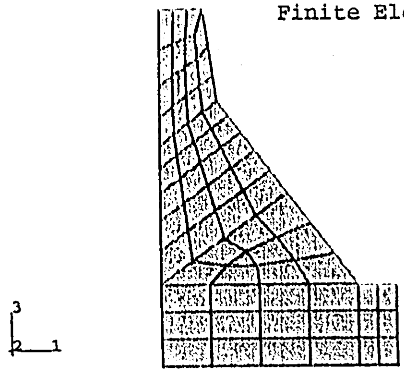


Figure d2

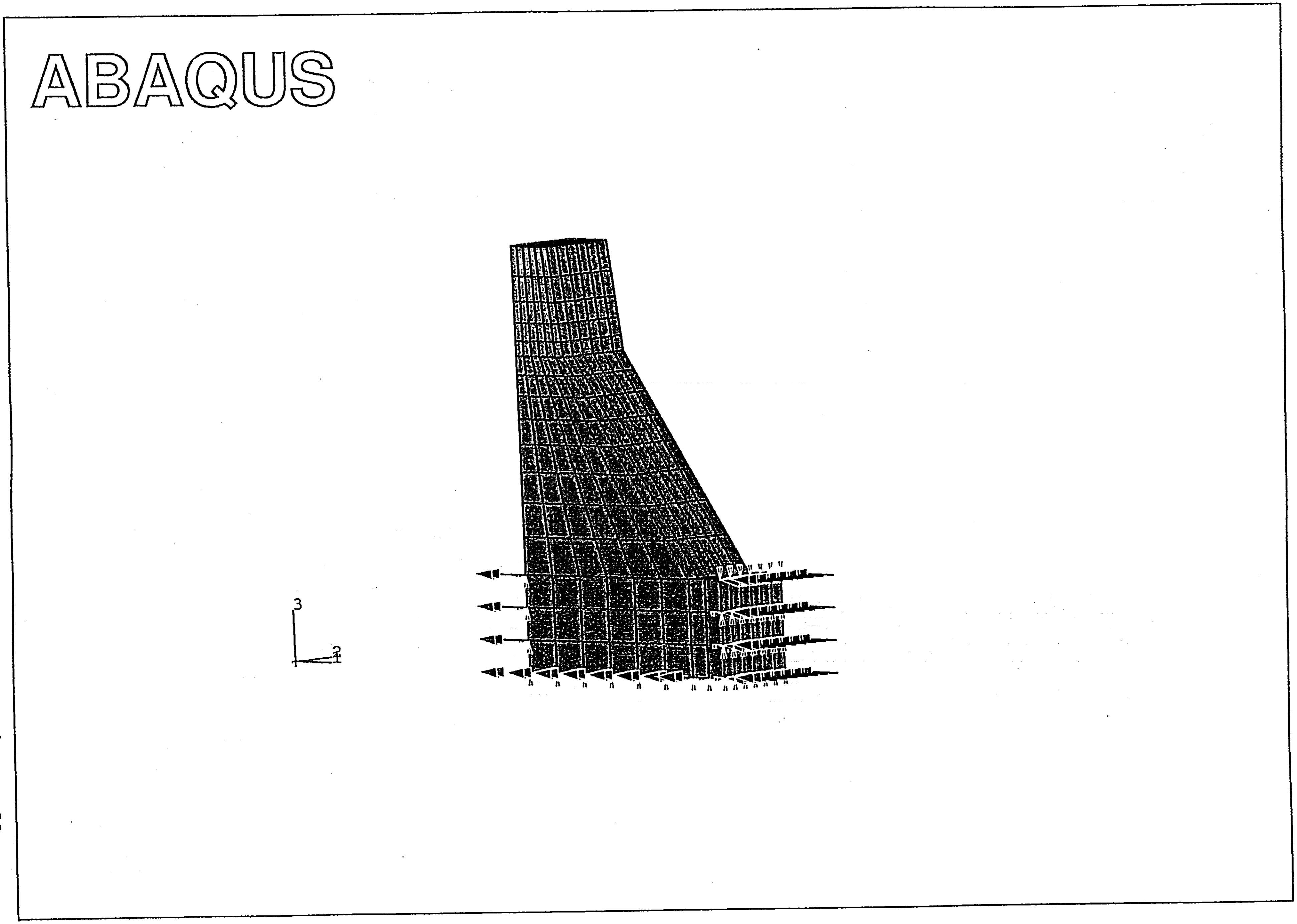


Figure d3

ABAQUS

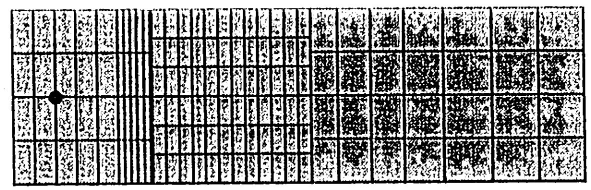
Koyna Laboratory Model Study
Locations of Instrumentation
Uncracked Model Study

Laboratory Test Model

Instrument	Elevation	Face	Corresponding Node
Accel04	49.6 inches	Upstream	503
Accel05	71.5 inches	Upstream	1534
Accel06	81.6 inches	Upstream	1955
Accel07	103.6 inches	Upstream	2075
Accel08	103.6 inches	Top	2085
LVDT01	23.6 inches	Downstream	298
LVDT02	49.6 inches	Upstream	503
LVDT03	61.6 inches	Downstream	1135
LVDT04	90.1 inches	Downstream	2010

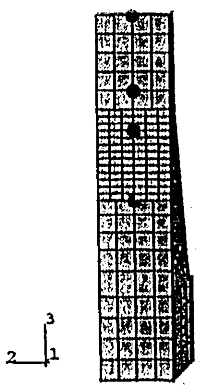
ABAQUS

Location of Nodes in ABAQUS Model (Mesh #1)
Used for Comparisons
of Disp. and Accel. Time Histories
Vertical Accelerometer ACCEL08



Plan View - Node 2085 - Center of Top Face

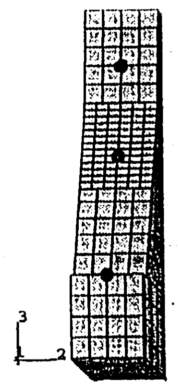
ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #1)
Elev. View - Vertical Face
Used for Comparisons of
Disp. and Accel. Time Histories
Horizontal Accelerometers

Node	Elevation
2075	103.6 inches
1955	82.3 inches
1534	70.9 inches
503	50.9 inches

ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #1)
Elev. View
Downstream (Sloped) Face
Used for Comparisons of
Disp. and Accel. Time Histories

Horizontal LVDT's

Node	Elevation
2010	87.6 inches
1135	60.8 inches
298	23.6 inches

Figure d4

ABAQUS

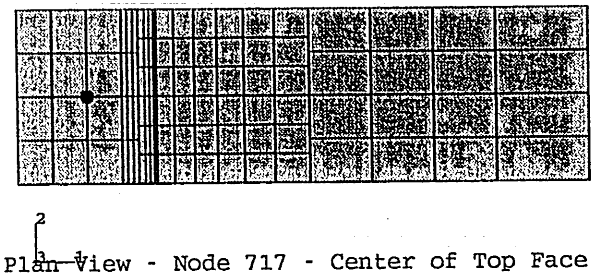
Koyna Laboratory Model Study
Locations of Instrumentation
Uncracked Model Study

Laboratory Test Model

Instrument	Elevation	Face	Corresponding Node
Accel04	49.6 inches	Upstream	118
Accel05	71.5 inches	Upstream	267
Accel06	81.6 inches	Upstream	610
Accel07	103.6 inches	Upstream	707
Accel08	103.6 inches	Top	717
LVDT01	23.6 inches	Downstream	8
LVDT02	49.6 inches	Upstream	118
LVDT03	61.6 inches	Downstream	407
LVDT04	90.1 inches	Downstream	762

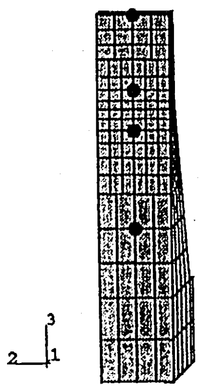
ABAQUS

Location of Nodes in ABAQUS Model (Mesh #2)
Used for Comparisons
of Disp. and Accel. Time Histories
Vertical Accelerometer ACCEL08



Plan View - Node 717 - Center of Top Face

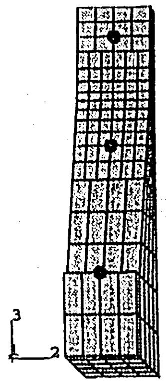
ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #2)
Elev. View - Vertical Face
Used for Comparisons of
Disp. and Accel. Time Histories
Horizontal Accelerometers

Node	Elevation
707	103.6 inches
610	82.3 inches
267	70.9 inches
118	43.1 inches

ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #2)
Elev. View
Downstream (Sloped) Face
Used for Comparisons of
Disp. and Accel. Time Histories

Horizontal LVDT's

Node	Elevation
762	95.1 inches
407	63.2 inches
8	23.6 inches

Figure d5

ABAQUS

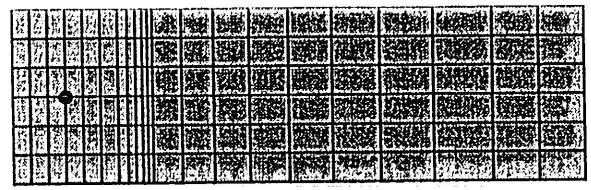
Koyna Laboratory Model Study
Locations of Instrumentation
Uncracked Model Study

Laboratory Test Model

Instrument	Elevation	Face	Corresponding Node
Accel04	49.6 inches	Upstream	519
Accel05	71.5 inches	Upstream	419
Accel06	81.6 inches	Upstream	204
Accel07	103.6 inches	Upstream	176
Accel08	103.6 inches	Top	179
LVDT01	23.6 inches	Downstream	859
LVDT02	49.6 inches	Upstream	519
LVDT03	61.6 inches	Downstream	511
LVDT04	90.1 inches	Downstream	196

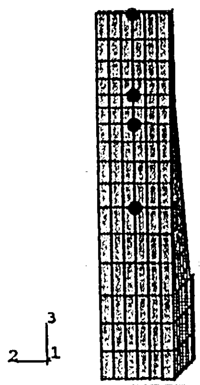
ABAQUS

Location of Nodes in ABAQUS Model (Mesh#3)
Used for Comparisons
of Disp. and Accel. Time Histories
Vertical Accelerometer ACCEL08



Plan View - Node 179 - Center of Top Face

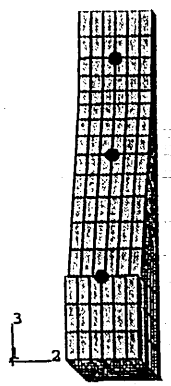
ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #3)
Elev. View - Vertical Face
Used for Comparisons of
Disp. and Accel. Time Histories
Horizontal Accelerometers

Node	Elevation
176	103.6 inches
204	80.6 inches
491	72.3 inches
519	48.6 inches

ABAQUS



Location of Nodes in
ABAQUS Model (Mesh#3)
Elev. View
Downstream (Sloped) Face
Used for Comparisons of
Disp. and Accel. Time Histories

Horizontal LVDT's

Node	Elevation
196	90.1 inches
511	61.6 inches
859	23.6 inches

Figure d6

ABAQUS

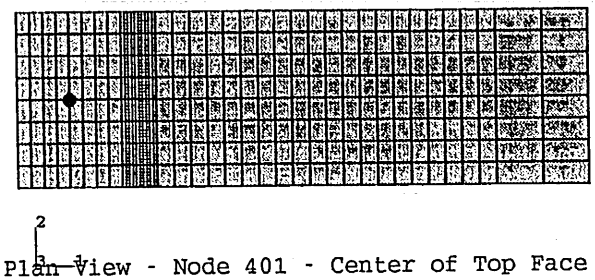
Koyna Laboratory Model Study
Locations of Instrumentation
Uncracked Model Study

Laboratory Test Model

Instrument	Elevation	Face	Corresponding Node
Accel04	49.6 inches	Upstream	118
Accel05	71.5 inches	Upstream	267
Accel06	81.6 inches	Upstream	610
Accel07	103.6 inches	Upstream	707
Accel08	103.6 inches	Top	717
LVDT01	23.6 inches	Downstream	8
LVDT02	49.6 inches	Upstream	118
LVDT03	61.6 inches	Downstream	407
LVDT04	90.1 inches	Downstream	762

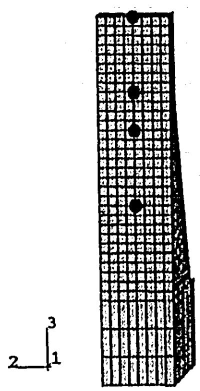
ABAQUS

Location of Nodes in ABAQUS Model (Mesh #4)
Used for Comparisons
of Disp. and Accel. Time Histories
Vertical Accelerometer ACCEL08



Plan View - Node 401 - Center of Top Face

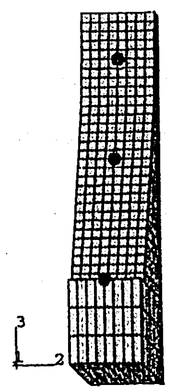
ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #2)
Elev. View - Vertical Face
Used for Comparisons of
Disp. and Accel. Time Histories
Horizontal Accelerometers

Node	Elevation
397	103.6 inches
469	82.2 inches
1621	71.6 inches
1693	50.3 inches

ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #4)
Elev. View
Downstream (Sloped) Face
Used for Comparisons of
Disp. and Accel. Time Histories

Horizontal LVDT's

Node	Elevation
450	90.3 inches
1665	60.9 inches
2788	23.6 inches

Figure d7

ABAQUS

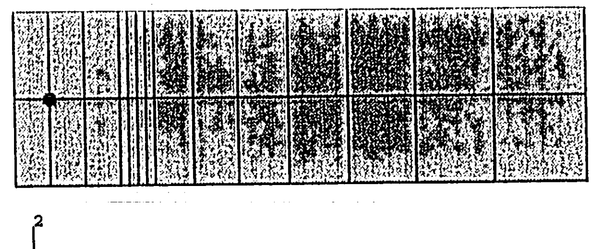
Koyna Laboratory Model Study
Locations of Instrumentation
Uncracked Model Study

Laboratory Test Model

Instrument	Elevation	Face	Corresponding Node
Accel04	49.6 inches	Upstream	118
Accel05	71.5 inches	Upstream	267
Accel06	81.6 inches	Upstream	610
Accel07	103.6 inches	Upstream	707
Accel08	103.6 inches	Top	717
LVDT01	23.6 inches	Downstream	8
LVDT02	49.6 inches	Upstream	118
LVDT03	61.6 inches	Downstream	407
LVDT04	90.1 inches	Downstream	762

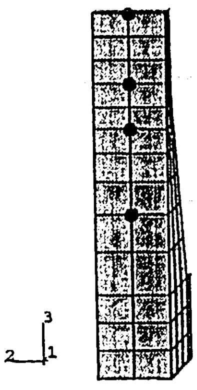
ABAQUS

Location of Nodes in ABAQUS Model (Mesh #5)
Used for Comparisons
of Disp. and Accel. Time Histories
Vertical Accelerometer ACCEL08



Plan View - Node 22 - Center of Top Face

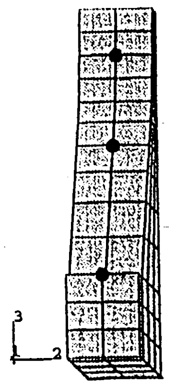
ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #5)
Elev. View - Vertical Face
Used for Comparisons of
Disp. and Accel. Time Histories
Horizontal Accelerometers

Node	Elevation
21	103.6 inches
33	83.6 inches
85	70.7 inches
97	46.4 inches

ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #5)
Elev. View
Downstream (Sloped) Face
Used for Comparisons of
Disp. and Accel. Time Histories

Horizontal LVDT's

Node	Elevation
32	90.3 inches
92	63.8 inches
173	23.6 inches

Figure d8

ABAQUS

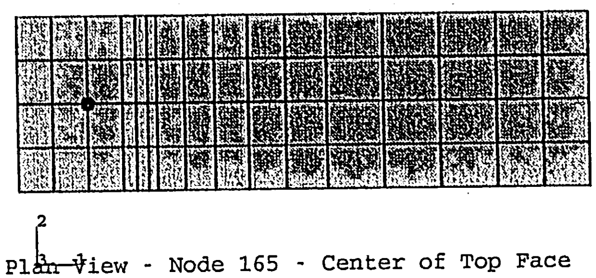
Koyna Laboratory Model Study
Locations of Instrumentation
Uncracked Model Study

Laboratory Test Model

Instrument	Elevation	Face	Corresponding Node
Accel04	49.6 inches	Upstream	196
Accel05	71.5 inches	Upstream	104
Accel06	81.6 inches	Upstream	124
Accel07	103.6 inches	Upstream	163
Accel08	103.6 inches	Top	165
LVDT01	23.6 inches	Downstream	289
LVDT02	49.6 inches	Upstream	196
LVDT03	61.6 inches	Downstream	232
LVDT04	90.1 inches	Downstream	140

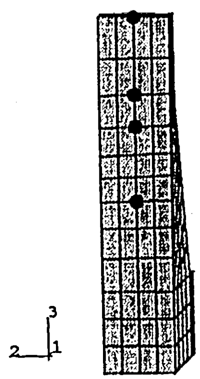
ABAQUS

Location of Nodes in ABAQUS Model (Mesh#6)
Used for Comparisons
of Disp. and Accel. Time Histories
Vertical Accelerometer ACCEL08



Plan View - Node 165 - Center of Top Face

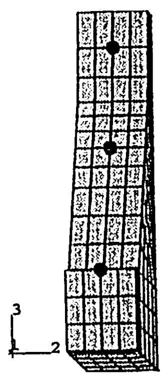
ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #6)
Elev. View - Vertical Face
Used for Comparisons of
Disp. and Accel. Time Histories
Horizontal Accelerometers

Node	Elevation
163	103.6 inches
124	80.8 inches
104	71.5 inches
196	49.8 inches

ABAQUS



Location of Nodes in
ABAQUS Model (Mesh#6)
Elev. View
Downstream (Sloped) Face
Used for Comparisons of
Disp. and Accel. Time Histories

Horizontal LVDT's

Node	Elevation
140	92.8 inches
232	62.5 inches
289	23.6 inches

Figure d9

Appendix E
Sensitivity of Results to the Number of Modes Extracted in the Frequency Analysis

ABAQUS

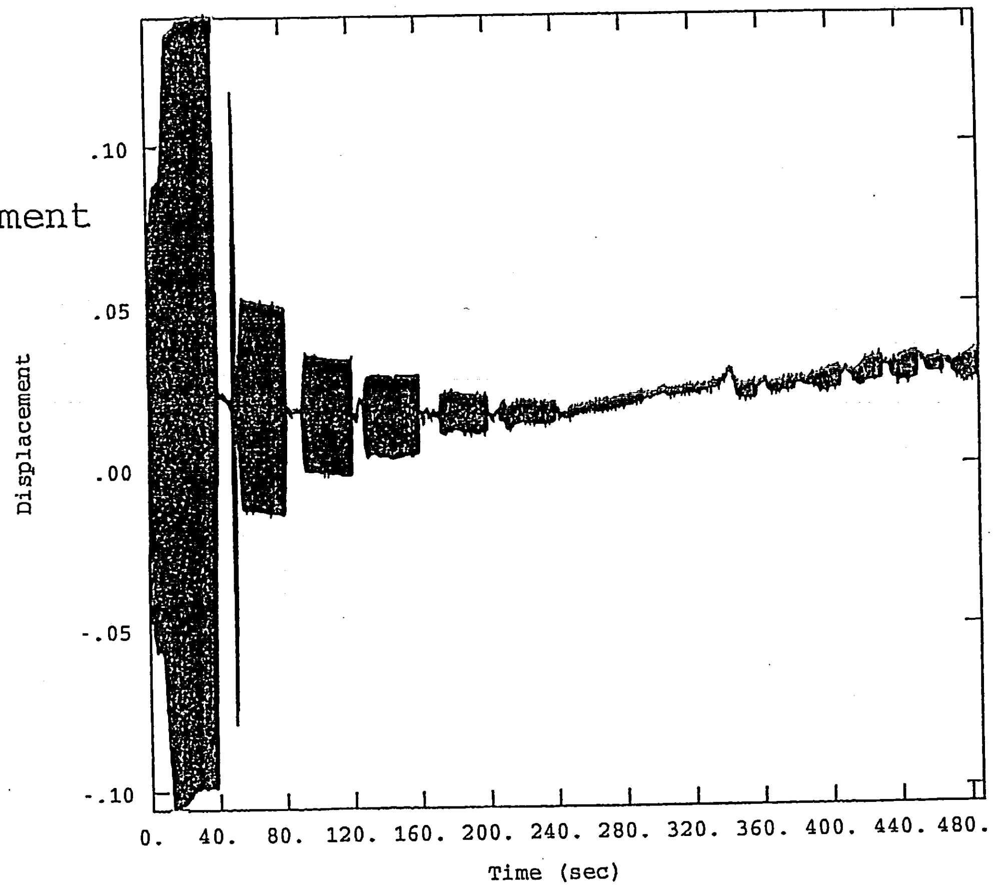
— ACTLVDT

LVDT Displacement

Record In

Actuator

(inches)



XMIN .000E+00
XMAX 4.862E+02
YMIN -1.056E-01
YMAX 1.397E-01

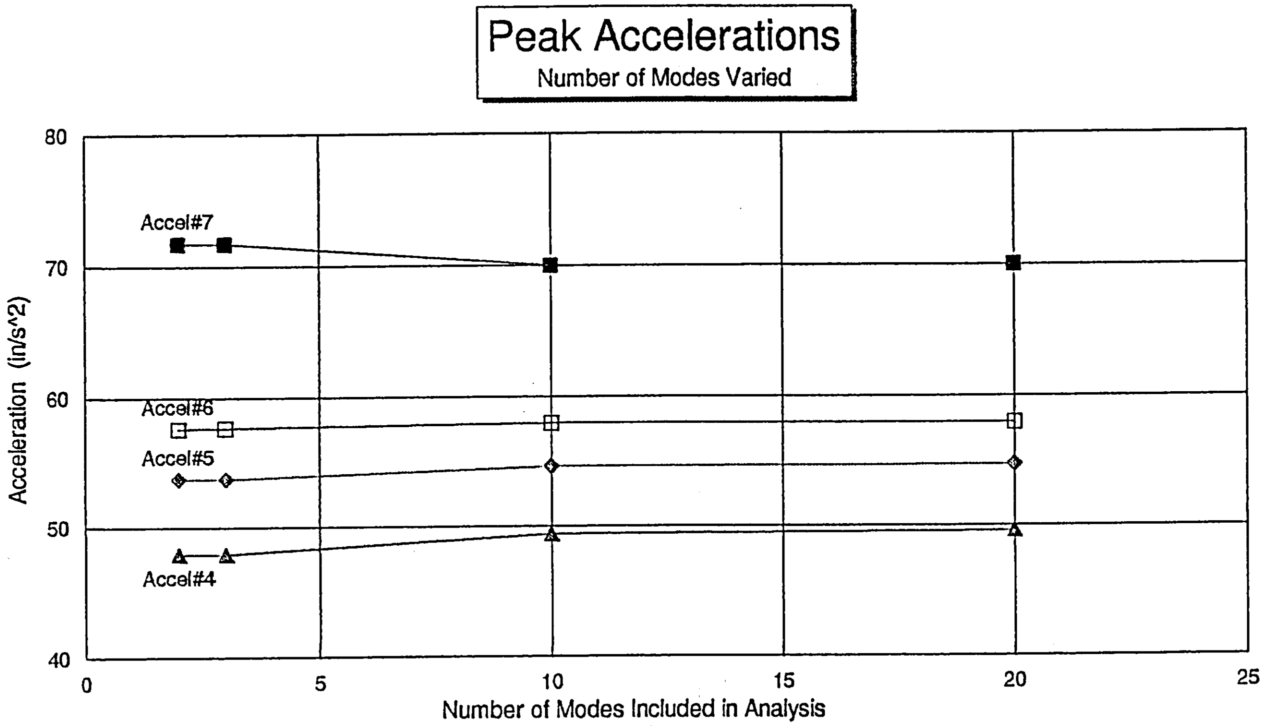
Figure e1

Uncracked Koyna Laboratory Study
Determination of the Number of Modes Required
Mesh#3

Material Properties

E = 150 ksi
Material Density = 138.2 pcf

Damping = 5% critical
Rayleigh Damping Factors
Alpha=2.827433,Beta=.000318



Peak Accelerations (inch / sec ^ 2)					
Number of Modes Used	2	3	10	20	LAB
Accel#7	71.71	71.71	69.98	69.99	53.26
Accel#6	57.60	57.66	57.99	57.99	51.72
Accel#5	53.67	53.67	54.55	54.64	49.26
Accel#4	47.89	47.89	49.35	49.56	47.72
CPU Time (sec)	53.04	56.91	163.21	210.94	

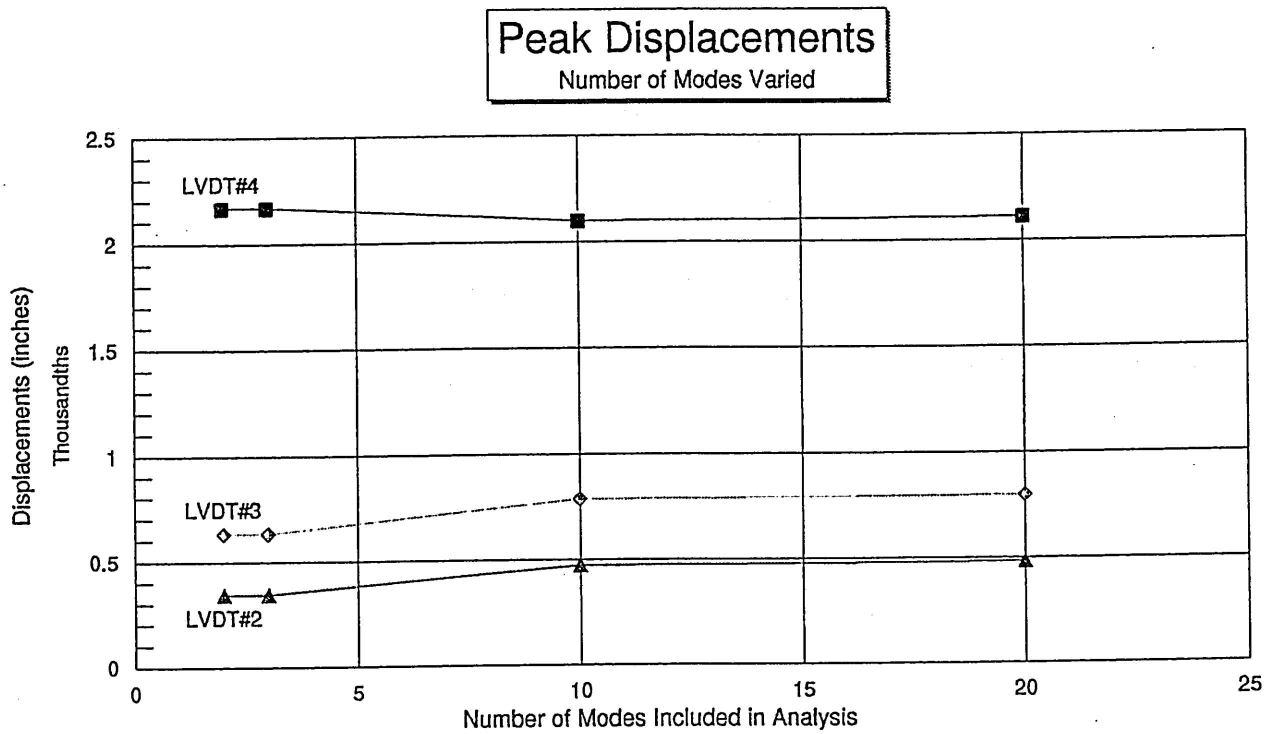
Figure e2

Uncracked Koyna Laboratory Study
Determination of the Number of Modes Required
Mesh#3

Material Properties

E = 150 ksi
Material Density = 138.2 pcf

Damping = 5% critical
Rayleigh Damping Factors
Alpha=2.827433,Beta=.000318



Peak Displacements (inches)					
Number of Modes Used	2	3	10	20	LAB
LVDT#4	2.2E-03	2.2E-03	2.1E-03	2.1E-03	7.2E-04
LVDT#3	6.3E-04	6.3E-04	7.9E-04	7.9E-04	3.1E-04
LVDT#2	3.4E-04	3.4E-04	4.7E-04	4.8E-04	2.1E-04

Figure e3

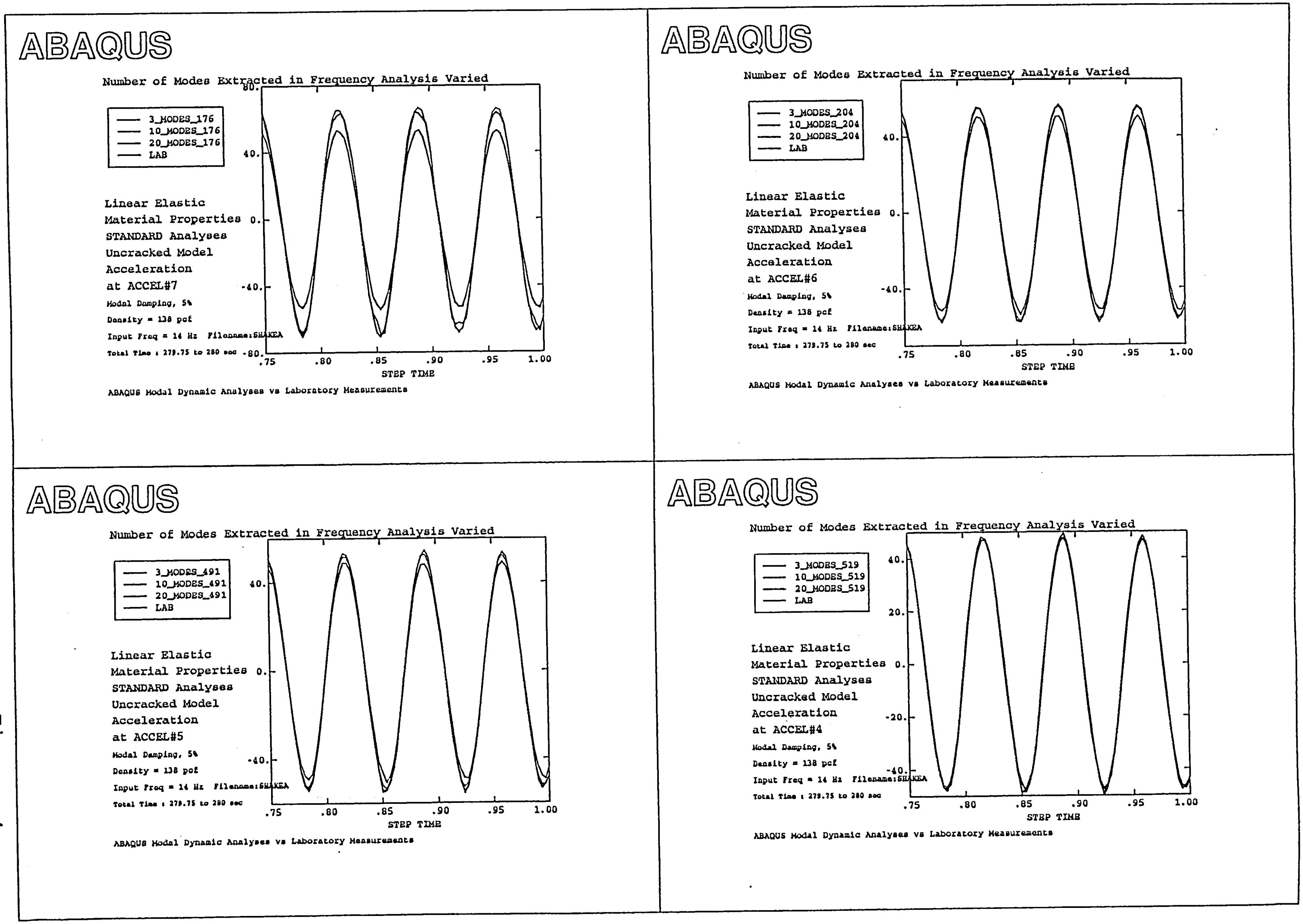

ABAQUS
Number of Modes Extracted in Frequency Analysis Varied
3_MODES_176
10_MODES_176
20_MODES_176
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Modal Damping, 5%
Density = 138 pcf
Input Freq = 14 Hz Filename:SHAKEA
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements
ABAQUS
Number of Modes Extracted in Frequency Analysis Varied
3_MODES_204
10_MODES_204
20_MODES_204
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Modal Damping, 5%
Density = 138 pcf
Input Freq = 14 Hz Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements
ABAQUS
Number of Modes Extracted in Frequency Analysis Varied
3_MODES_491
10_MODES_491
20_MODES_491
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Modal Damping, 5%
Density = 138 pcf
Input Freq = 14 Hz Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements
ABAQUS
Number of Modes Extracted in Frequency Analysis Varied
3_MODES_519
10_MODES_519
20_MODES_519
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Modal Damping, 5%
Density = 138 pcf
Input Freq = 14 Hz Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
20.
0.
-20.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

Figure e4

Appendix F
Sensitivity to Variation in Mesh Definition

Uncracked Koyna Laboratory Study
Determination of Mesh Sensitivity
Six Different Mesh Densities Evaluated

Material Properties

Elastic Modulus = 150,000 psi
Material Density = 138.2 pcf

Damping = 5% critical
Rayleigh Damping Factors
Alpha = 2.827433; Beta = .000318

Natural Frequencies (Hz)

Mode	Mesh#5	Mesh#6	Mesh#2	Mesh#1	Mesh#3	Mesh#4
1	14.1	14.8	15.4	15.5	15.7	15.7
2	28.7	29.2	29.0	29.3	29.9	30.2
3	33.7	49.4	43.6	53.8	54.2	54.4
4	38.0	55.9	51.3	68.3	64.5	70.2
5	40.5	57.8	52.4	74.6	67.3	76.3
6	42.7	59.8	58.2	88.5	69.4	78.5
7	46.9	60.3	59.3	90.5	73.7	81.5
8	48.4	63.0	67.2	91.2	74.6	84.7
9	49.1	63.2	74.6	93.3	75.4	88.2
10	49.1	66.7	88.6	94.0	76.8	91.2

Peak Accelerations (inch / sec ^ 2)

Instrument	Mesh#5	Mesh#6	Mesh#2	Mesh#1	Mesh#3	Mesh#4
Accel#7	71.0	71.4	69.5	70.2	70.0	69.4
Accel#6	58.8	57.5	58.4	58.5	58.0	58.8
Accel#5	52.9	53.3	54.5	54.3	54.6	54.6
Accel#4	47.9	48.2	48.4	49.8	49.4	49.9

Peak Displacements (inches)

Instrument	Mesh#5	Mesh#6	Mesh#2	Mesh#1	Mesh#3	Mesh#4
LVDT#4	2.5E-03	2.5E-03	2.6E-03	2.1E-03	2.1E-03	2.1E-03
LVDT#3	8.2E-04	7.3E-04	9.0E-04	7.8E-04	7.9E-04	7.6E-04
LVDT#2	1.5E-04	4.1E-04	3.7E-04	5.4E-04	4.7E-04	5.1E-04

CPU Seconds

	Mesh#5	Mesh#6	Mesh#2	Mesh#1	Mesh#3	Mesh#4
CPU Sec	20.48	105.79	208.34	895.43	163.21	446.58

Figure f1

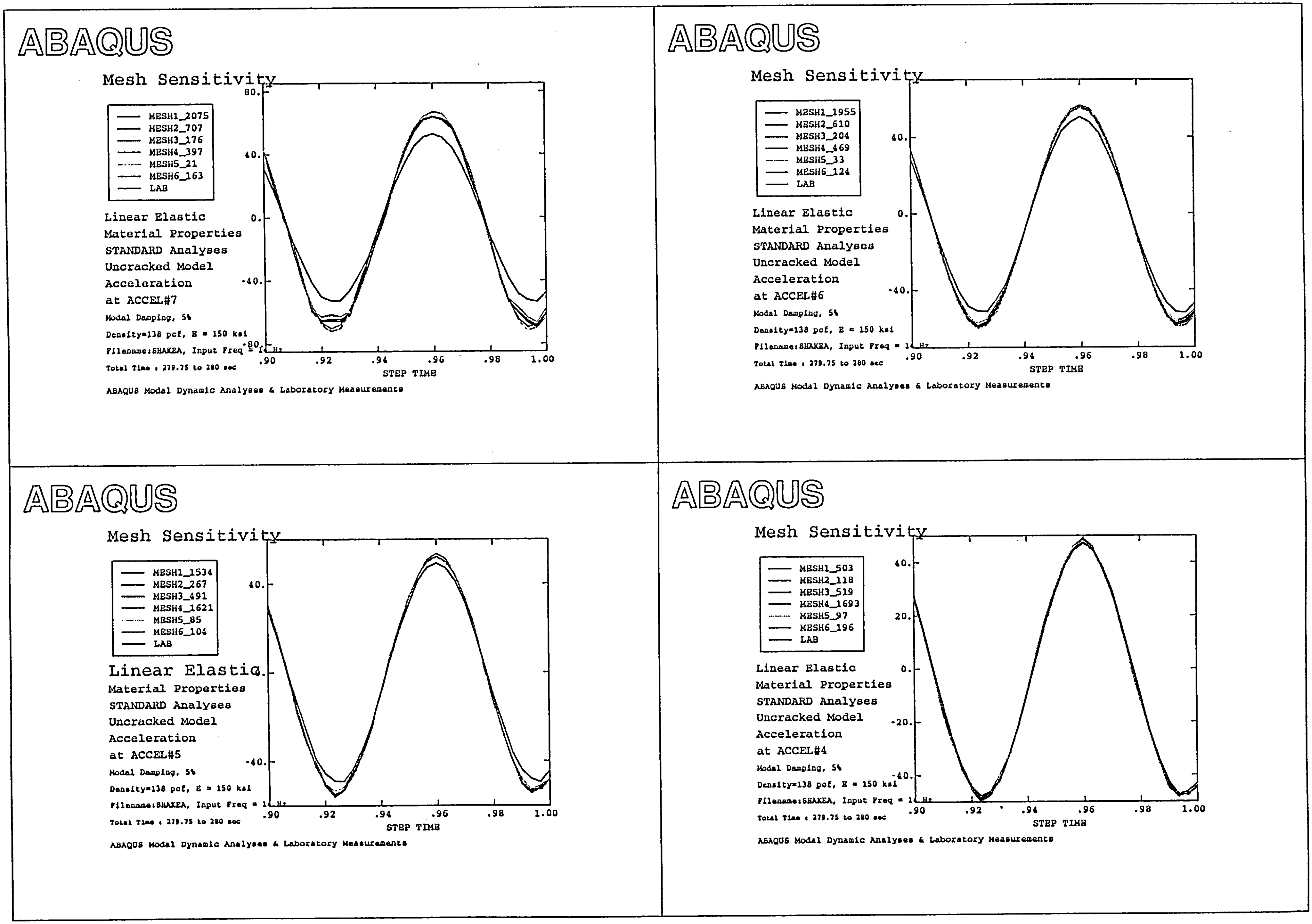

ABAQUS
Mesh Sensitivity
MESH1_2075
MESH2_707
MESH3_176
MESH4_397
MESH5_21
MESH6_163
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Modal Damping, 5%
Density=138 pcf, E = 150 ksi
Filename:SHAKEA, Input Freq = 1 Hz
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses & Laboratory Measurements
ABAQUS
Mesh Sensitivity
MESH1_1955
MESH2_610
MESH3_204
MESH4_469
MESH5_33
MESH6_124
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Modal Damping, 5%
Density=138 pcf, E = 150 ksi
Filename:SHAKEA, Input Freq = 1 Hz
Total Time : 279.75 to 280 sec
40.
0.
-40.
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses & Laboratory Measurements
ABAQUS
Mesh Sensitivity
MESH1_1534
MESH2_267
MESH3_491
MESH4_1621
MESH5_85
MESH6_104
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Modal Damping, 5%
Density=138 pcf, E = 150 ksi
Filename:SHAKEA, Input Freq = 1 Hz
Total Time : 279.75 to 280 sec
40.
0.
-40.
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses & Laboratory Measurements
ABAQUS
Mesh Sensitivity
MESH1_503
MESH2_118
MESH3_519
MESH4_1693
MESH5_97
MESH6_196
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Modal Damping, 5%
Density=138 pcf, E = 150 ksi
Filename:SHAKEA, Input Freq = 1 Hz
Total Time : 279.75 to 280 sec
40.
20.
0.
-20.
-40.
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses & Laboratory Measurements

Figure E2

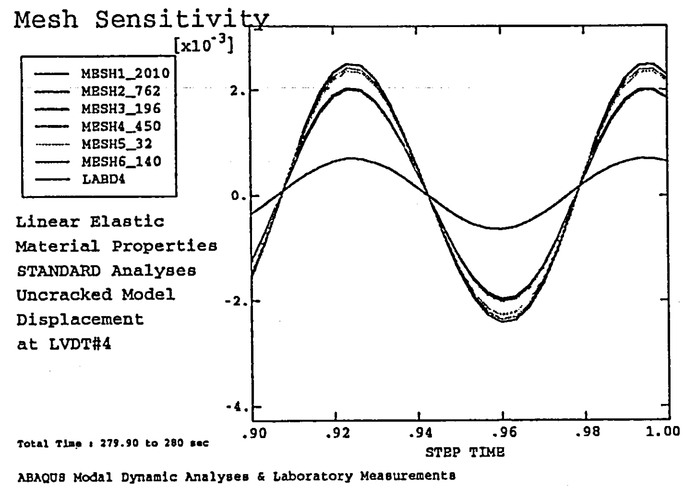
ABAQUS

Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Mesh Density

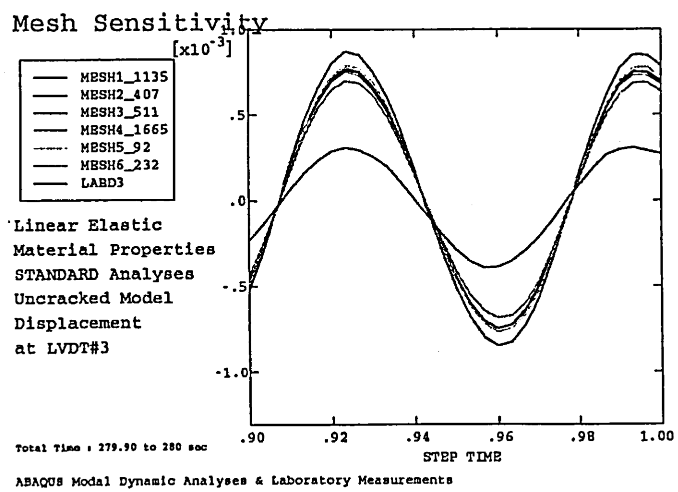
Comparison of Displacements
ABAQUS STANDARD
Modal Dynamic Analysis

Input Record SHAKEA
Modal Damping, 3.5%
Elastic Modulus = 150 ksi
Density = 138.2 pcf

ABAQUS



ABAQUS



ABAQUS

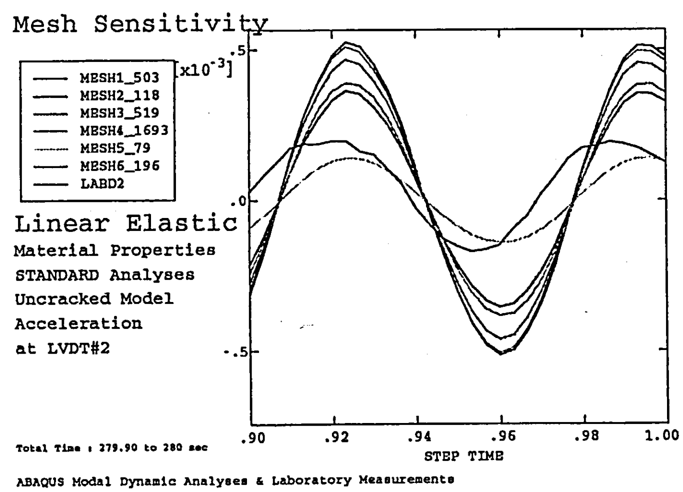


Figure E3

Uncracked Koyna Laboratory Study
Determination of Mesh Sensitivity
Six Different Mesh Densities Evalusted

Material Properties

Elastic Modulus = 150,000 psi
Material Density = 138.2 pcf

Damping = 5% of critical
Rayleigh Damping Factors
Alpha = 2.827433; Beta = .000318

Whole Model Energy Quantities

	"Artificial" Strain Energy "hourglass control"	Total Strain Energy	Kinetic Energy	External Work	Total Energy Balence
Mesh#1					
Static	0.00496	2.45500	0.00000	2.45500	-0.00001500
Dynamic	0.00000	2.45500	0.00646	2.72500	-0.00001500
Response Spectrum	0.00000	1.80000	0.00000	0.00000	-0.00000841
Mesh#2					
Static	0.01096	2.55300	0.00000	2.55300	-0.00001600
Dynamic	0.00000	2.55300	0.00728	0.67020	-0.00001600
Response Spectrum	0.00000	1.87000	0.00000	0.00000	-0.00000851
Mesh#3					
Static	0.00981	2.51600	0.00000	2.51600	-0.00001600
Dynamic	0.00000	2.51600	0.00568	0.55240	-0.00001600
Response Spectrum	0.00000	1.84000	0.00000	0.00000	-0.00000853
Mesh#4					
Static	0.00552	2.51600	0.00000	2.51600	-0.00001600
Dynamic	0.00000	2.51600	0.00538	2.63800	-0.00001600
Response Spectrum	0.00000	1.84000	0.00000	0.00000	-0.00000867
Mesh#5					
Static	0.02687	2.53900	0.00000	2.53900	-0.00001490
Dynamic	0.00000	2.53900	0.00793	-0.57200	-0.00001490
Response Spectrum	0.00000	1.86000	0.00000	0.00000	-0.00000795
Mesh#6					
Static	0.15860	4.43900	0.00000	4.43900	-0.00002500
Dynamic	0.00000	4.43900	0.00716	4.43900	-0.00002500
Response Spectrum	0.00000	3.25400	0.00000	0.00000	-0.00001327

Figure f4

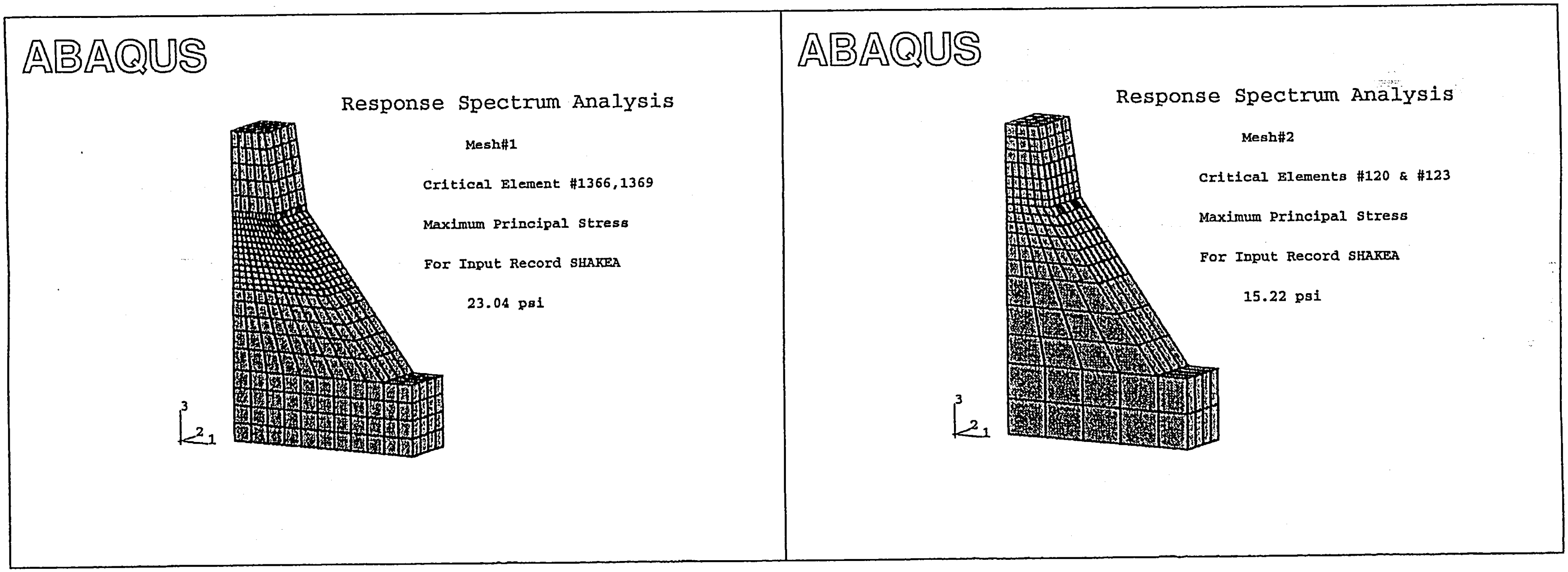

ABAQUS
Response Spectrum Analysis
Mesh#1
Critical Element #1366,1369
Maximum Principal Stress
For Input Record SHAKEA
23.04 psi
ABAQUS
Response Spectrum Analysis
Mesh#2
Critical Elements #120 & #123
Maximum Principal Stress
For Input Record SHAKEA
15.22 psi

Figure f5

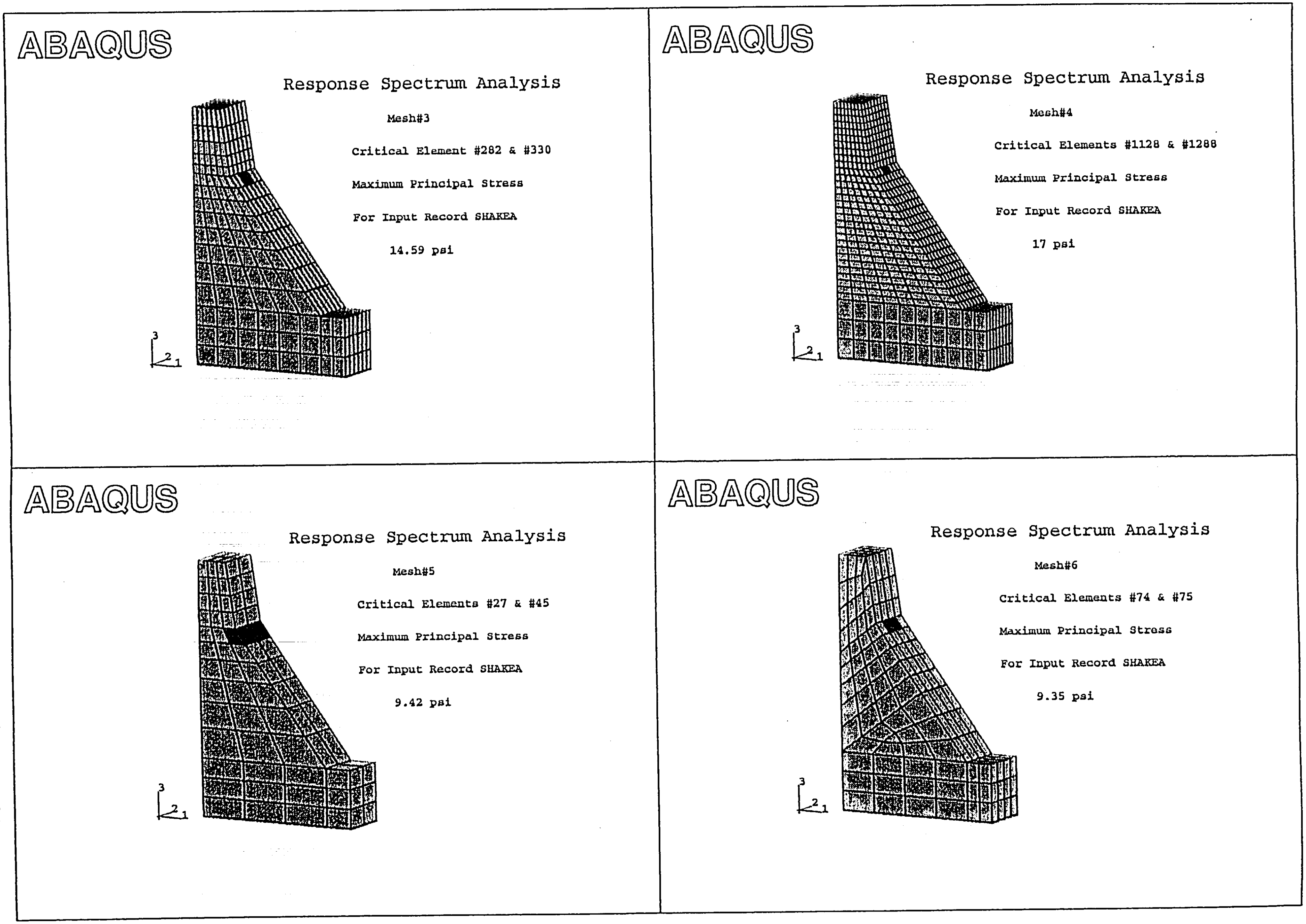

ABAQUS
Response Spectrum Analysis
Mesh#3
Critical Element #282 & #330
Maximum Principal Stress
For Input Record SHAKEA
14.59 psi
ABAQUS
Response Spectrum Analysis
Mesh#4
Critical Elements #1128 & #1288
Maximum Principal Stress
For Input Record SHAKEA
17 psi
ABAQUS
Response Spectrum Analysis
Mesh#5
Critical Elements #27 & #45
Maximum Principal Stress
For Input Record SHAKEA
9.42 psi
ABAQUS
Response Spectrum Analysis
Mesh#6
Critical Elements #74 & #75
Maximum Principal Stress
For Input Record SHAKEA
9.35 psi

Figure f6

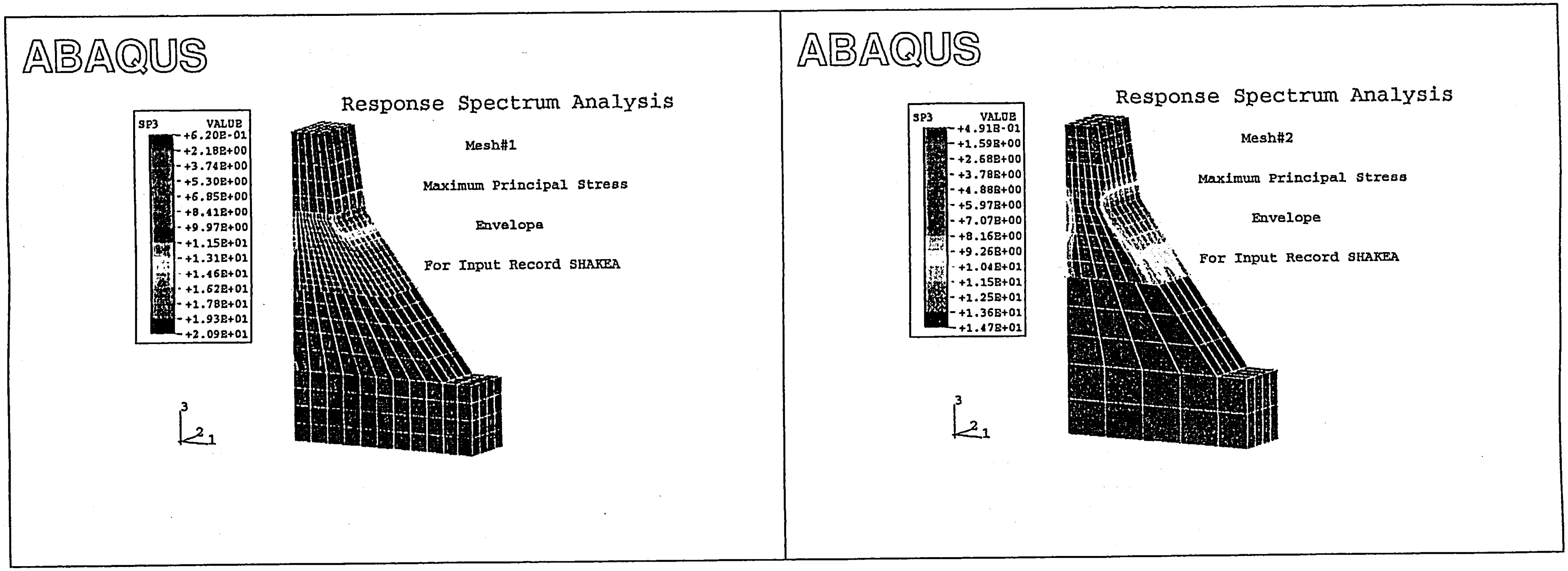

ABAQUS
Response Spectrum Analysis
Mesh#1
Maximum Principal Stress
Envelope
For Input Record SHAKEA
SP3 VALUE
+6.20E-01
+2.18E+00
+3.74E+00
+5.30E+00
+6.85E+00
+8.41E+00
+9.97E+00
+1.15E+01
+1.31E+01
+1.46E+01
+1.62E+01
+1.78E+01
+1.93E+01
+2.09E+01
3
2
1
ABAQUS
Response Spectrum Analysis
Mesh#2
Maximum Principal Stress
Envelope
For Input Record SHAKEA
SP3 VALUE
+4.91E-01
+1.59E+00
+2.68E+00
+3.78E+00
+4.88E+00
+5.97E+00
+7.07E+00
+8.16E+00
+9.26E+00
+1.04E+01
+1.15E+01
+1.25E+01
+1.36E+01
+1.47E+01
3
2
1

Figure f7

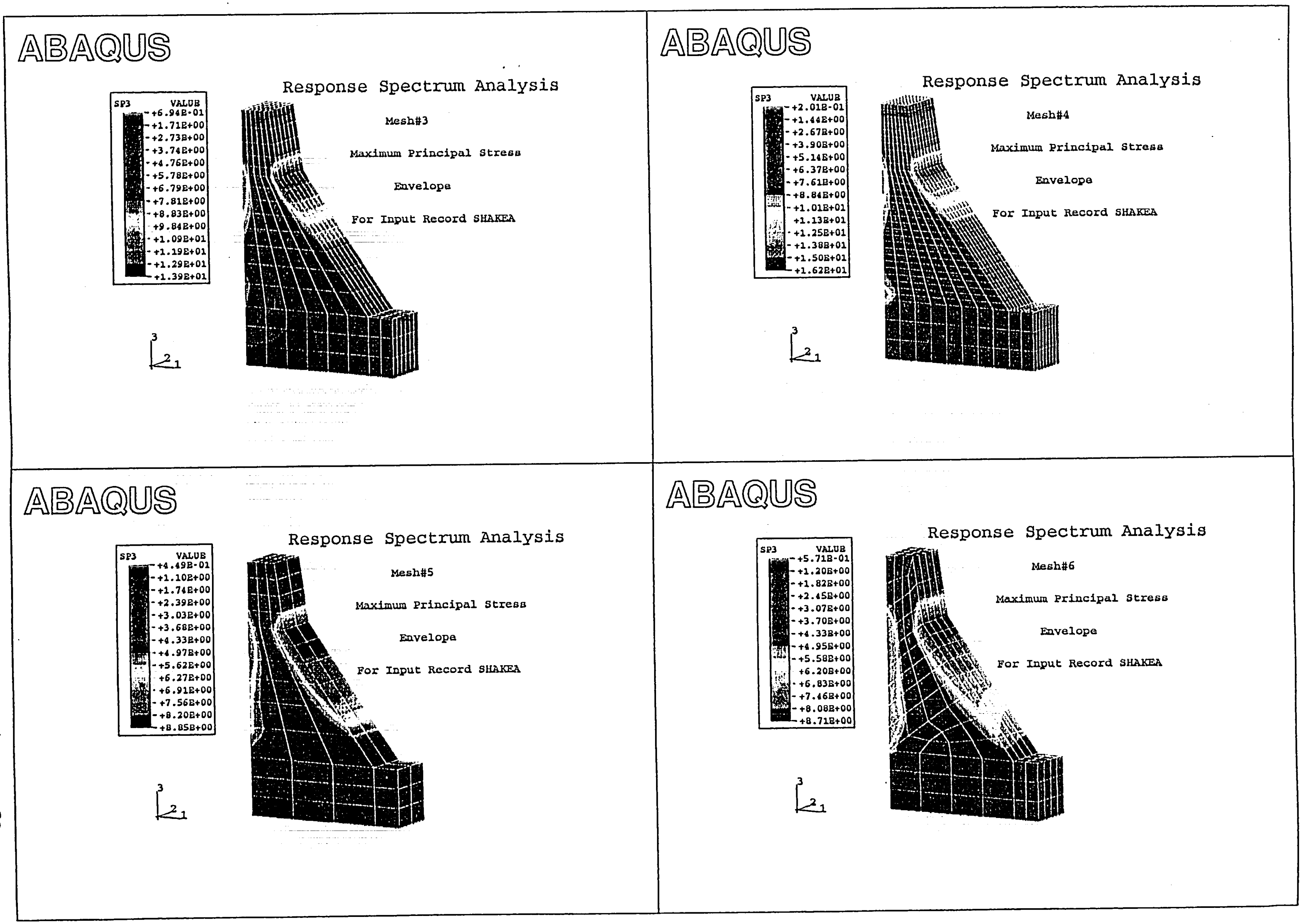

ABAQUS
Response Spectrum Analysis
Mesh#3
Maximum Principal Stress
Envelope
For Input Record SHAKEA
SP3 VALUE
+6.94E-01
+1.71E+00
+2.73E+00
+3.74E+00
+4.76E+00
+5.78E+00
+6.79E+00
+7.81E+00
+8.83E+00
+9.84E+00
+1.09E+01
+1.19E+01
+1.29E+01
+1.39E+01
ABAQUS
Response Spectrum Analysis
Mesh#4
Maximum Principal Stress
Envelope
For Input Record SHAKEA
SP3 VALUE
+2.01E-01
+1.44E+00
+2.67E+00
+3.90E+00
+5.14E+00
+6.37E+00
+7.61E+00
+8.84E+00
+1.01E+01
+1.13E+01
+1.25E+01
+1.38E+01
+1.50E+01
+1.62E+01
ABAQUS
Response Spectrum Analysis
Mesh#5
Maximum Principal Stress
Envelope
For Input Record SHAKEA
SP3 VALUE
+4.49E-01
+1.10E+00
+1.74E+00
+2.39E+00
+3.03E+00
+3.68E+00
+4.33E+00
+4.97E+00
+5.62E+00
+6.27E+00
+6.91E+00
+7.56E+00
+8.20E+00
+8.85E+00
ABAQUS
Response Spectrum Analysis
Mesh#6
Maximum Principal Stress
Envelope
For Input Record SHAKEA
SP3 VALUE
+5.71E-01
+1.20E+00
+1.82E+00
+2.45E+00
+3.07E+00
+3.70E+00
+4.33E+00
+4.95E+00
+5.58E+00
+6.20E+00
+6.83E+00
+7.46E+00
+8.08E+00
+8.71E+00

Figure f8

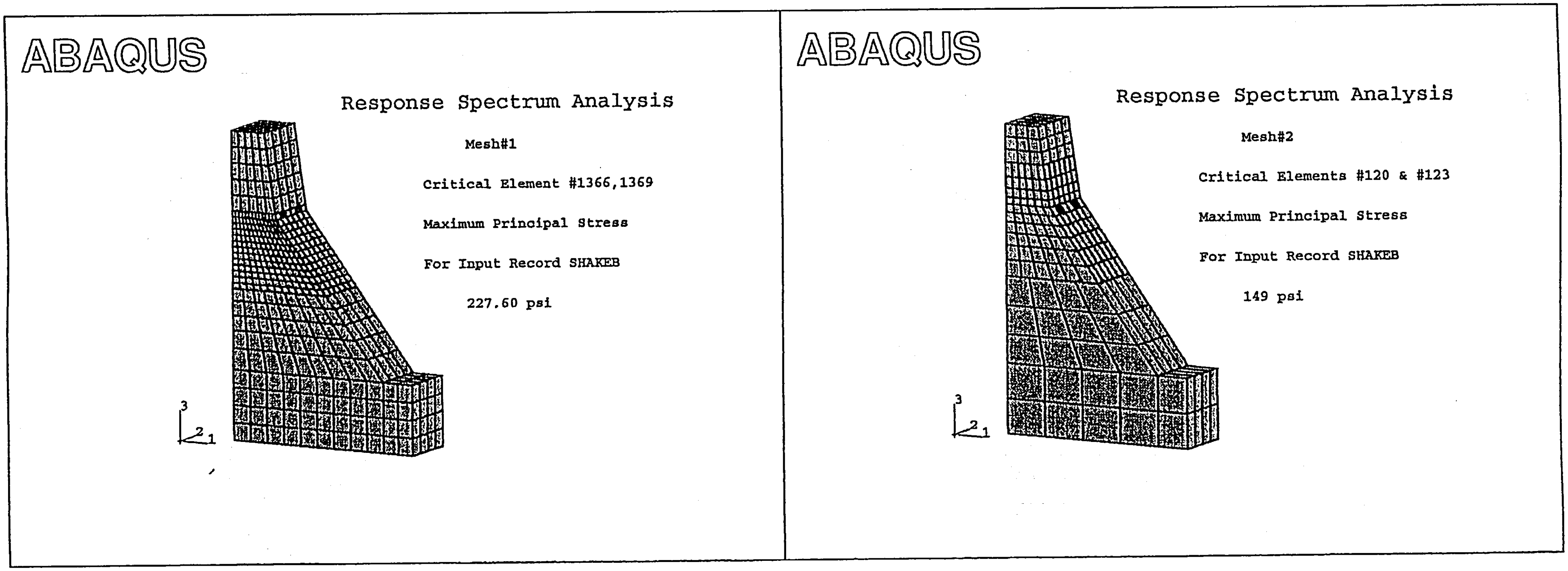

ABAQUS
Response Spectrum Analysis
Mesh#1
Critical Element #1366,1369
Maximum Principal Stress
For Input Record SHAKEB
227.60 psi
3
2
1
ABAQUS
Response Spectrum Analysis
Mesh#2
Critical Elements #120 & #123
Maximum Principal Stress
For Input Record SHAKEB
149 psi
3
2
1

Figure f9

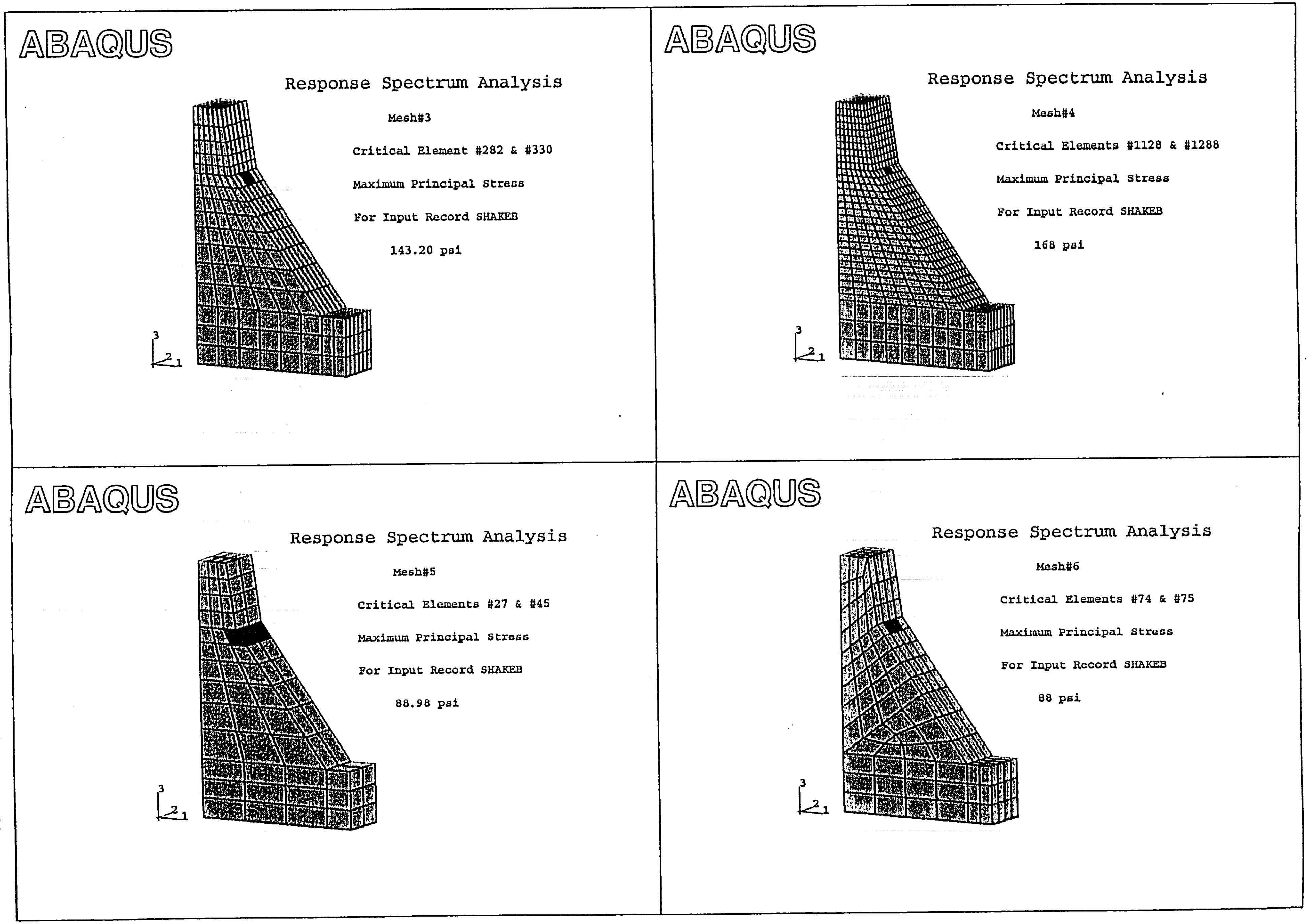

ABAQUS
Response Spectrum Analysis
Mesh#3
Critical Element #282 & #330
Maximum Principal Stress
For Input Record SHAKEB
143.20 psi
ABAQUS
Response Spectrum Analysis
Mesh#4
Critical Elements #1128 & #1288
Maximum Principal Stress
For Input Record SHAKEB
168 psi
ABAQUS
Response Spectrum Analysis
Mesh#5
Critical Elements #27 & #45
Maximum Principal Stress
For Input Record SHAKEB
88.98 psi
ABAQUS
Response Spectrum Analysis
Mesh#6
Critical Elements #74 & #75
Maximum Principal Stress
For Input Record SHAKEB
88 psi

Figure f10

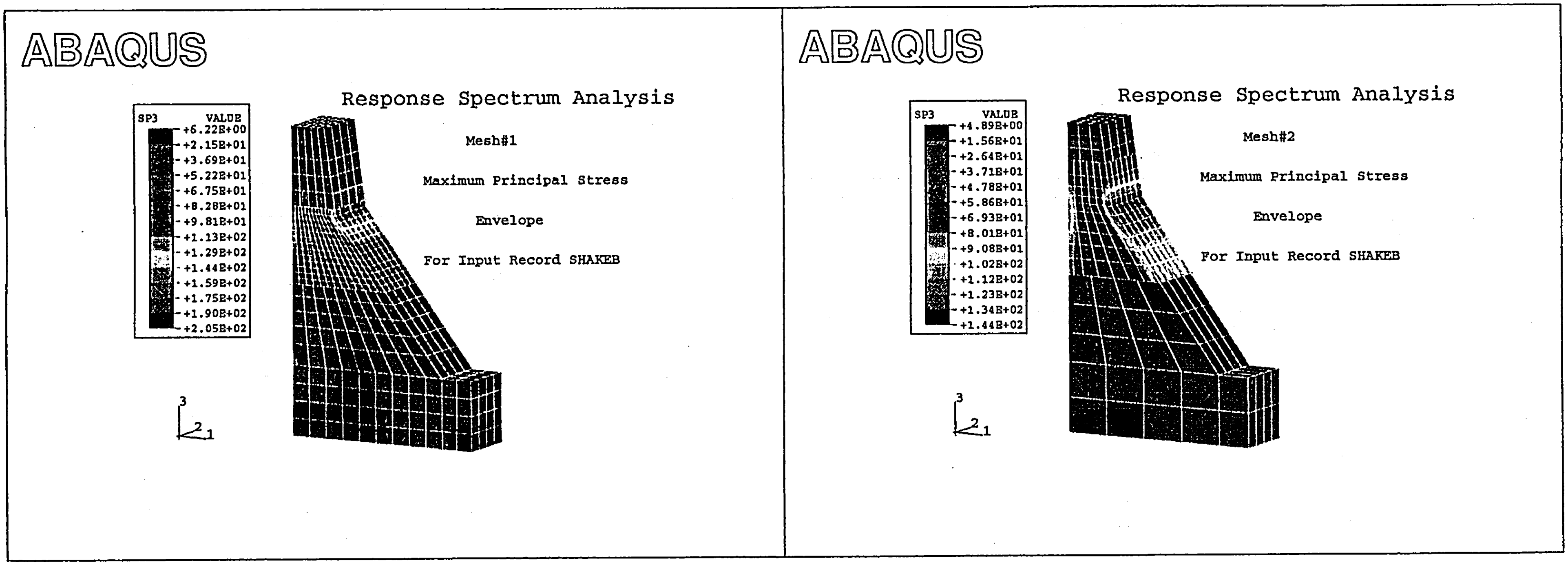

ABAQUS
Response Spectrum Analysis
Mesh#1
Maximum Principal Stress
Envelope
For Input Record SHAKEB
SP3 VALUE
+6.22E+00
+2.15E+01
+3.69E+01
+5.22E+01
+6.75E+01
+8.28E+01
+9.81E+01
+1.13E+02
+1.29E+02
+1.44E+02
+1.59E+02
+1.75E+02
+1.90E+02
+2.05E+02
3
2
1
ABAQUS
Response Spectrum Analysis
Mesh#2
Maximum Principal Stress
Envelope
For Input Record SHAKEB
SP3 VALUE
+4.89E+00
+1.56E+01
+2.64E+01
+3.71E+01
+4.78E+01
+5.86E+01
+6.93E+01
+8.01E+01
+9.08E+01
+1.02E+02
+1.12E+02
+1.23E+02
+1.34E+02
+1.44E+02
3
2
1

Figure f11

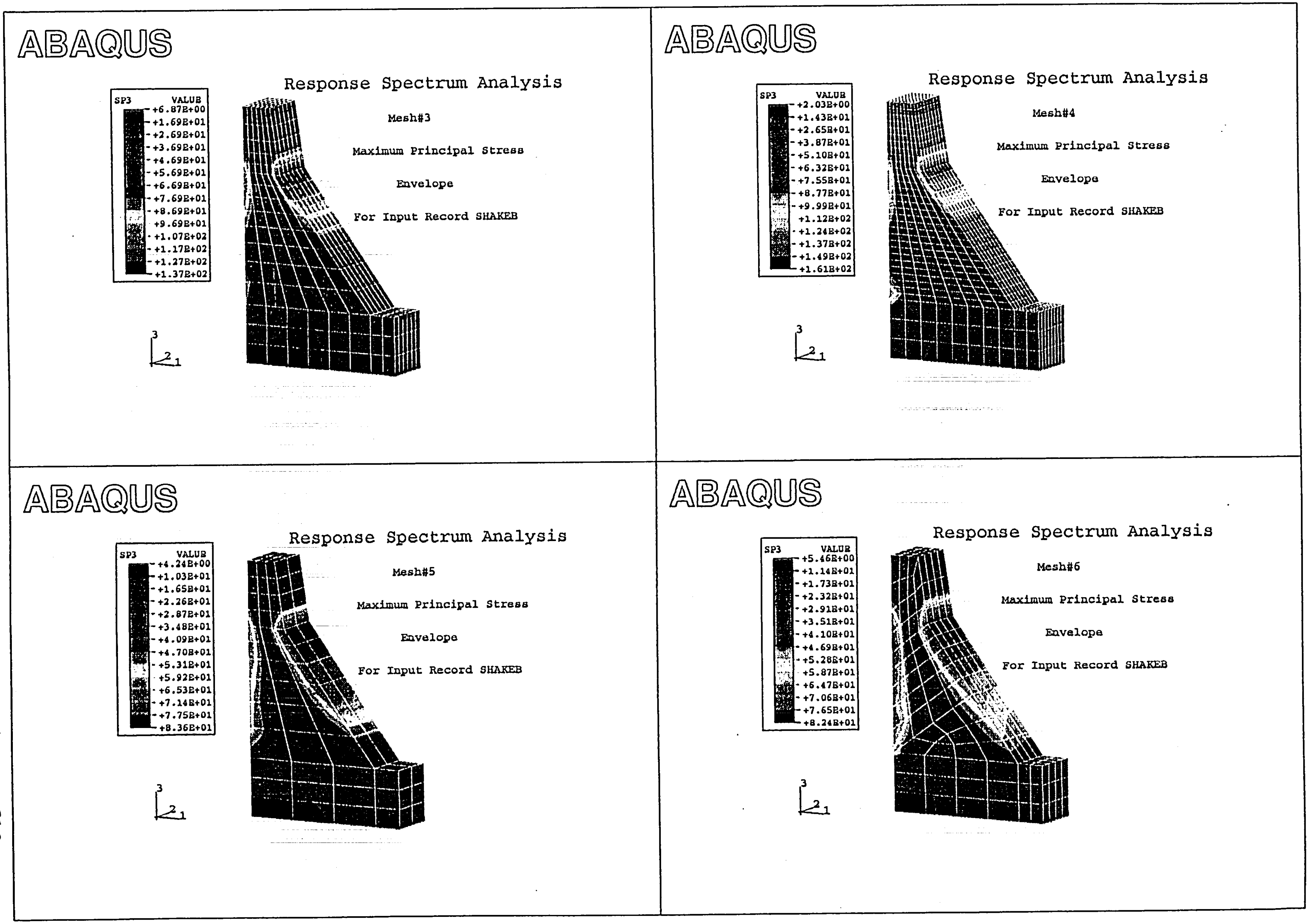

ABAQUS
Response Spectrum Analysis
Mesh#3
Maximum Principal Stress
Envelope
For Input Record SHAKEB
SP3 VALUE
+6.87E+00
+1.69E+01
+2.69E+01
+3.69E+01
+4.69E+01
+5.69E+01
+6.69E+01
+7.69E+01
+8.69E+01
+9.69E+01
+1.07E+02
+1.17E+02
+1.27E+02
+1.37E+02
ABAQUS
Response Spectrum Analysis
Mesh#4
Maximum Principal Stress
Envelope
For Input Record SHAKEB
SP3 VALUE
+2.03E+00
+1.43E+01
+2.65E+01
+3.87E+01
+5.10E+01
+6.32E+01
+7.55E+01
+8.77E+01
+9.99E+01
+1.12E+02
+1.24E+02
+1.37E+02
+1.49E+02
+1.61E+02
ABAQUS
Response Spectrum Analysis
Mesh#5
Maximum Principal Stress
Envelope
For Input Record SHAKEB
SP3 VALUE
+4.24E+00
+1.03E+01
+1.65E+01
+2.26E+01
+2.87E+01
+3.48E+01
+4.09E+01
+4.70E+01
+5.31E+01
+5.92E+01
+6.53E+01
+7.14E+01
+7.75E+01
+8.36E+01
ABAQUS
Response Spectrum Analysis
Mesh#6
Maximum Principal Stress
Envelope
For Input Record SHAKEB
SP3 VALUE
+5.46E+00
+1.14E+01
+1.73E+01
+2.32E+01
+2.91E+01
+3.51E+01
+4.10E+01
+4.69E+01
+5.28E+01
+5.87E+01
+6.47E+01
+7.06E+01
+7.65E+01
+8.24E+01

Figure f12

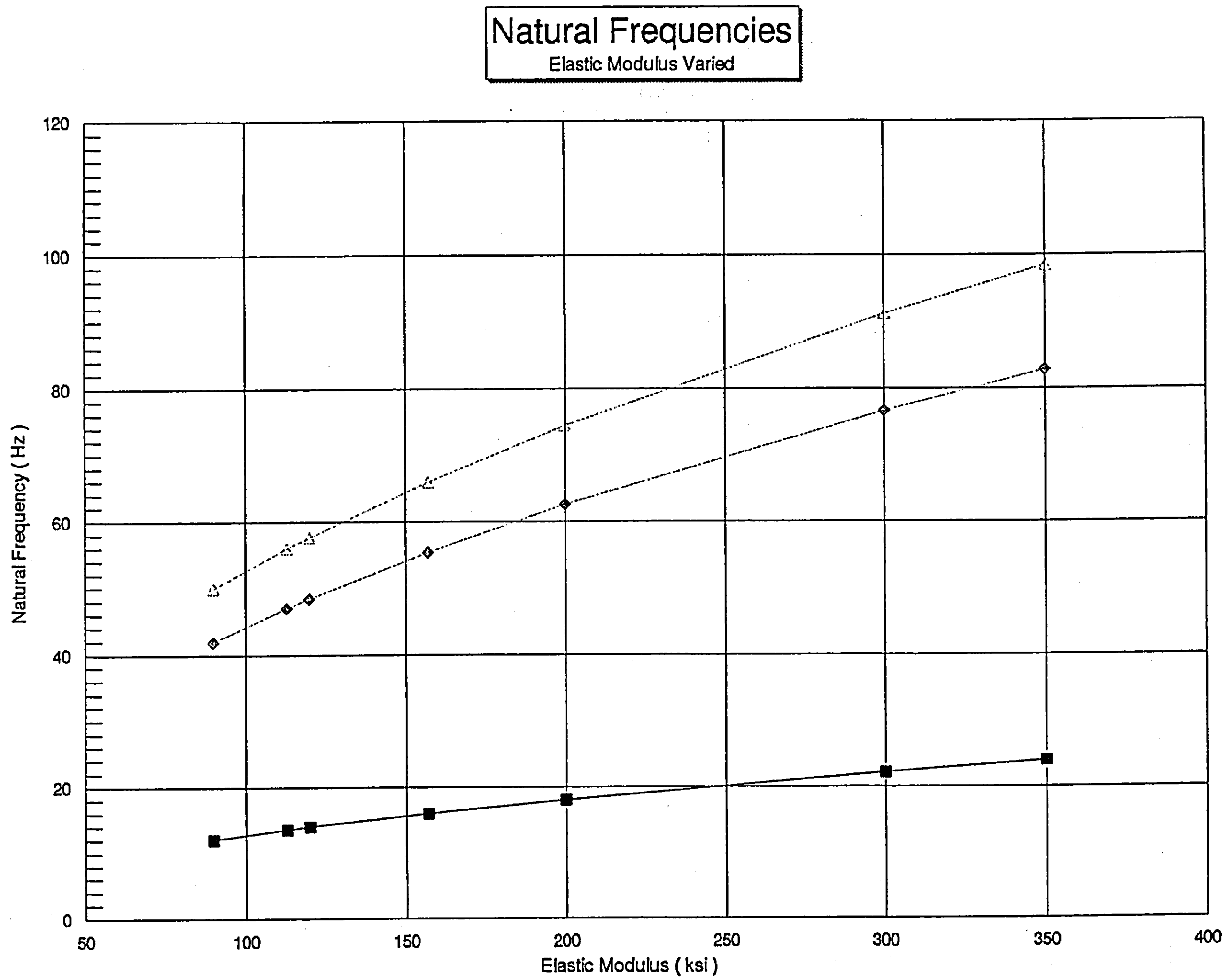
Appendix G
Sensitivity to Variation in Linear Elastic Material Properties

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3

Material Properties

E = (90, 113, 120, 157, 200, 300, 350 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Natural Frequencies (Hz)								
Mode	90	113	120	157	200	300	350	LAB
1	12.1	13.6	14.0	16.0	18.0	22.2	23.9	18.0
2	23.2	26.0	26.8	30.6	34.6	42.4	45.7	24.0
3	41.9	47.0	48.4	55.4	62.5	76.6	82.7	30.0
4	49.9	55.9	57.6	65.9	74.4	91.1	98.4	
5	52.1	58.4	60.2	68.8	77.7	95.2	102.8	
6	53.8	60.2	62.1	71.0	80.1	98.1	106.0	
7	57.1	64.0	65.9	75.4	85.1	104.2	112.6	
8	57.8	64.8	66.8	76.4	86.2	105.6	114.0	
9	58.4	65.4	67.4	77.1	87.0	106.6	115.1	
10	59.5	66.7	68.7	78.6	88.7	108.7	117.4	

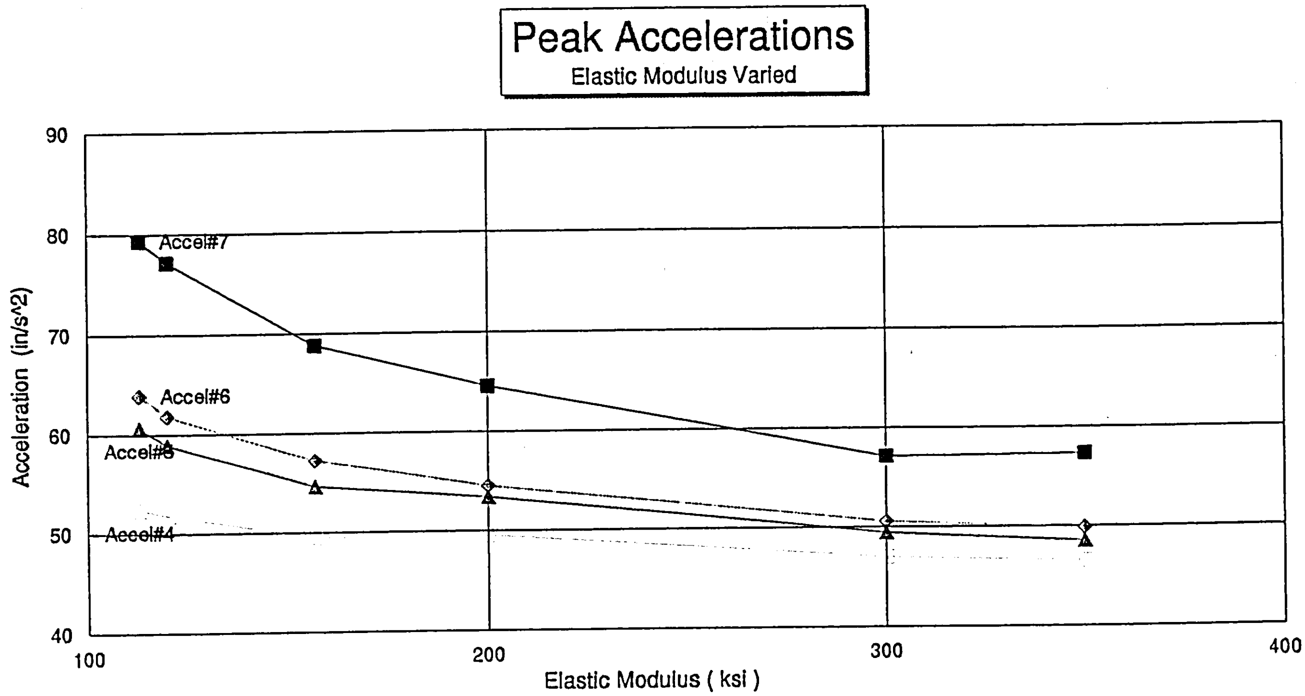
Figure g1

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3

Material Properties

E = (113, 120, 157, 200, 300, 350 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

	113	120	157	200	300	350	LAB
Accel#7	79.31	77.11	68.75	64.53	57.14	57.39	53.26
Accel#6	63.80	61.74	57.19	54.46	50.50	49.85	51.72
Accel#5	60.60	58.90	54.54	53.34	49.42	48.51	49.26
Accel#4	52.28	51.69	49.47	49.50	46.97	46.47	47.72

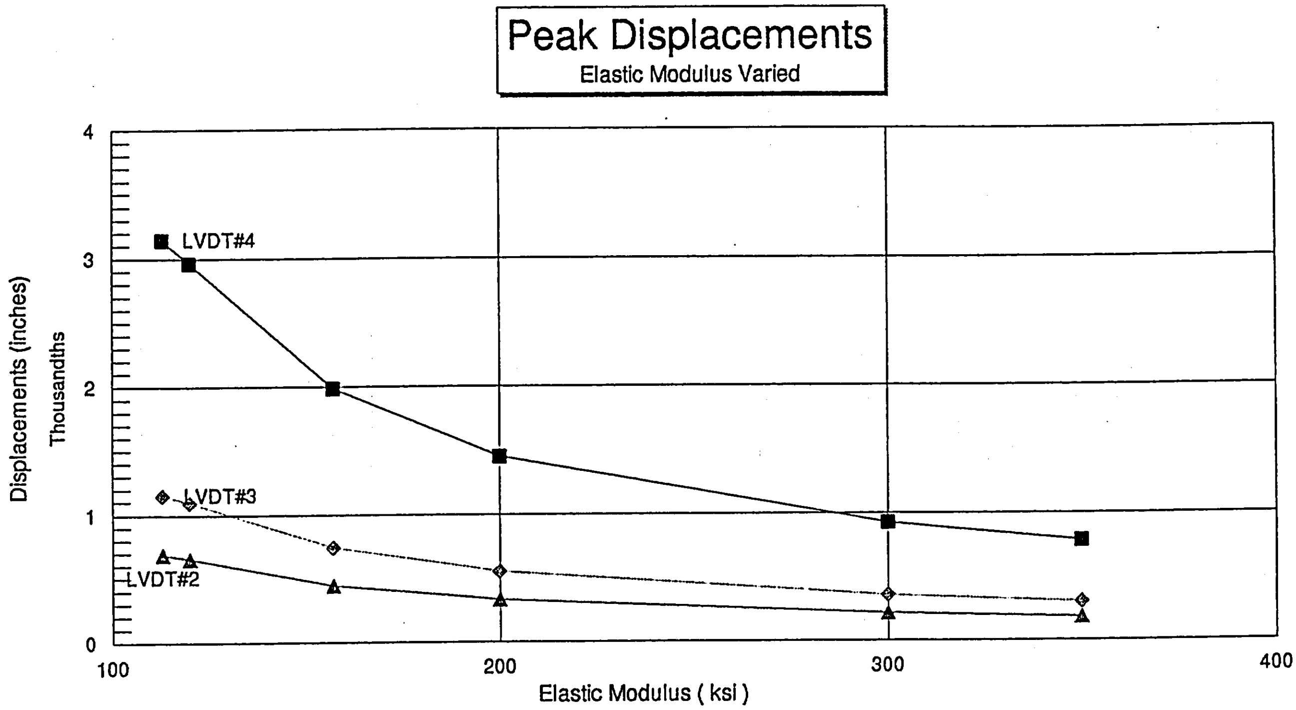
Figure g2

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3

Material Properties

E = (113, 120, 157, 200, 300, 350 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (inches)							
	113	120	157	200	300	350	LAB
LVDT#4	3.1E-03	3.0E-03	2.0E-03	1.5E-03	9.2E-04	7.8E-04	7.2E-04
LVDT#3	1.2E-03	1.1E-03	7.4E-04	5.5E-04	3.6E-04	3.0E-04	3.1E-04
LVDT#2	6.9E-04	6.5E-04	4.4E-04	3.3E-04	2.2E-04	1.8E-04	2.1E-04

Figure g3

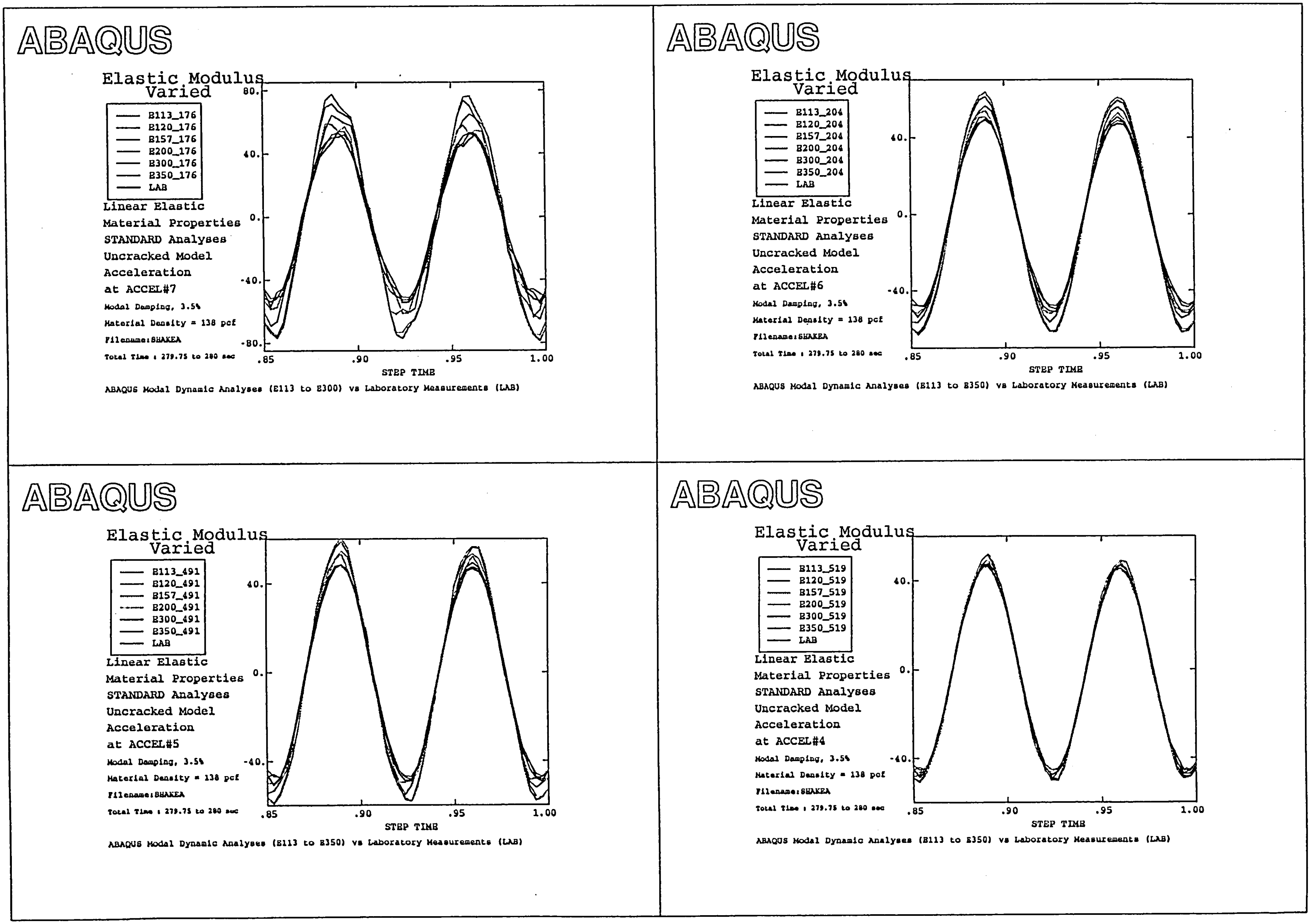
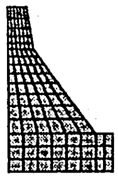

ABAQUS
Elastic Modulus Varied
E113_176
E120_176
E157_176
E200_176
E300_176
E350_176
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Modal Damping, 3.5%
Material Density = 138 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses (E113 to E300) vs Laboratory Measurements (LAB)
ABAQUS
Elastic Modulus Varied
E113_204
E120_204
E157_204
E200_204
E300_204
E350_204
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Modal Damping, 3.5%
Material Density = 138 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses (E113 to E350) vs Laboratory Measurements (LAB)
ABAQUS
Elastic Modulus Varied
E113_491
E120_491
E157_491
E200_491
E300_491
E350_491
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Modal Damping, 3.5%
Material Density = 138 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses (E113 to E350) vs Laboratory Measurements (LAB)
ABAQUS
Elastic Modulus Varied
E113_519
E120_519
E157_519
E200_519
E300_519
E350_519
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Modal Damping, 3.5%
Material Density = 138 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses (E113 to E350) vs Laboratory Measurements (LAB)

Figure 94

ABAQUS

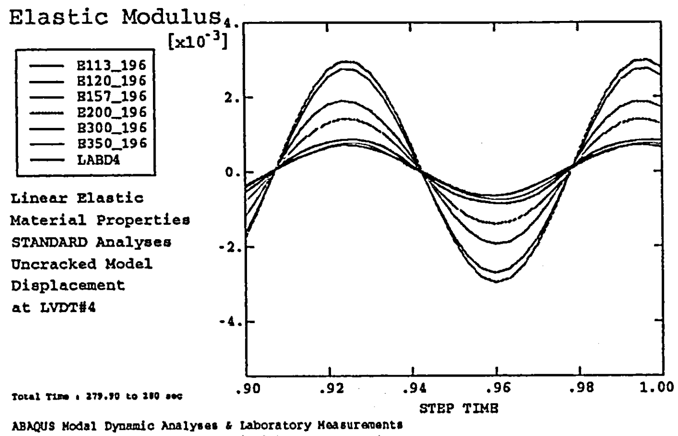
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus

Comparison of Displacements
ABAQUS STANDARD
Modal Dynamic Analysis

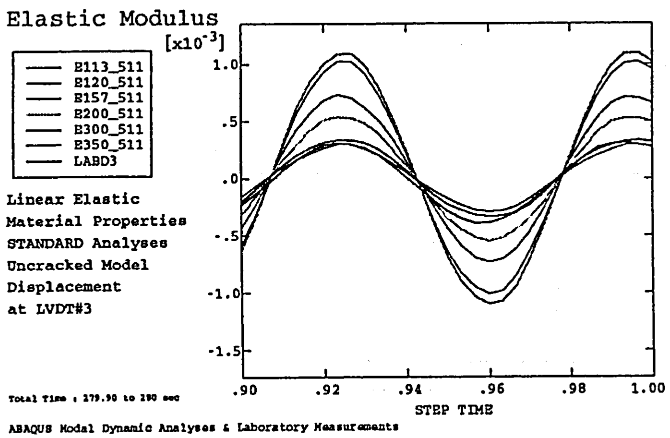


Input Record SHAKEA
Modal Damping, 3.5%
Density = 138.2 pcf
Mesh # 3

ABAQUS



ABAQUS



ABAQUS

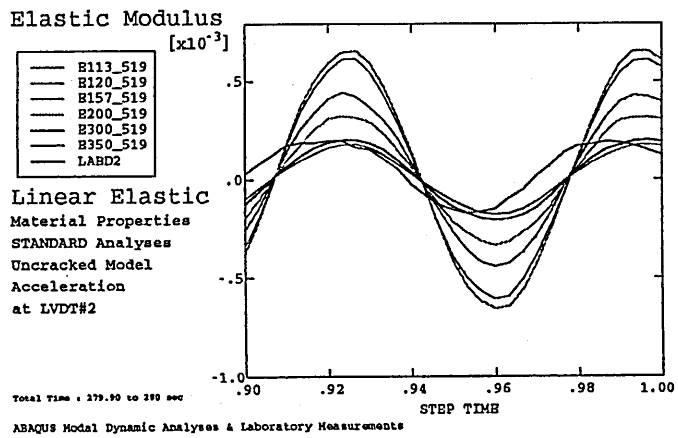


Figure 95

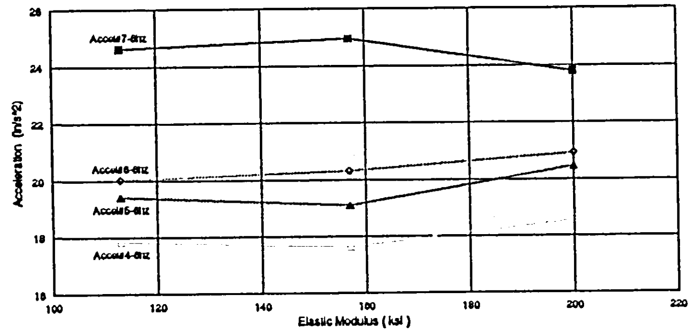
Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
6 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248

Peak Accelerations
Elastic Modulus Varied with 6 hz Input Motion



Peak Accelerations (inch / sec ^ 2)

10 hz Input	Motion	113	157	200	Lab	10 hz
	Accel#7-6hz	24.62	24.96	23.79	Accel#7-6hz	17.55
	Accel#6-6hz	20.02	20.31	20.93	Accel#6-6hz	17.86
	Accel#5-6hz	19.40	19.09	20.45	Accel#5-6hz	16.93
	Accel#4-6hz	17.84	17.65	18.56	Accel#4-6hz	17.24

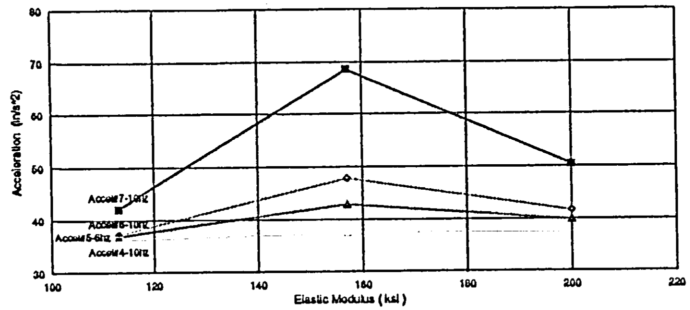
Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
10 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248

Peak Accelerations
Elastic Modulus Varied with 10 hz Input Motion



Peak Accelerations (inch / sec ^ 2)

10 hz Input	Motion	113	157	200	Lab	10 hz
	Accel#7-10hz	42.15	68.45	50.39	Accel#7-10hz	37.87
	Accel#6-10hz	37.18	47.84	41.61	Accel#6-10hz	36.94
	Accel#5-10hz	36.79	42.87	39.70	Accel#5-10hz	35.4
	Accel#4-10hz	36.27	37.47	37.50	Accel#4-10hz	36.02

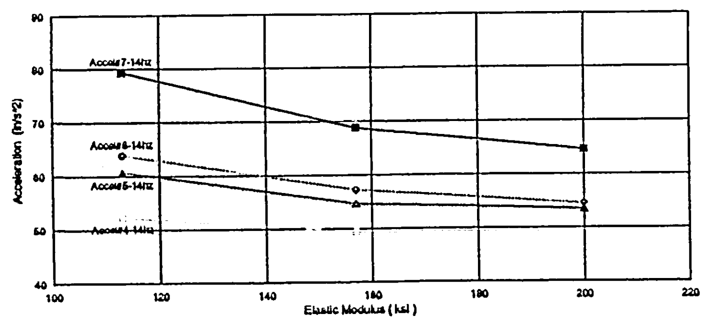
Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
14 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248

Peak Accelerations
Elastic Modulus Varied with 14 hz Input Motion



Peak Accelerations (inch / sec ^ 2)

14 hz Input	Motion	113	157	200	Lab	14 hz
	Accel#7-14hz	79.31	68.76	64.53	Accel#7-14hz	53.26
	Accel#6-14hz	63.80	57.19	54.46	Accel#6-14hz	50.72
	Accel#5-14hz	60.60	54.54	53.34	Accel#5-14hz	49.26
	Accel#4-14hz	52.28	49.47	49.5	Accel#4-14hz	47.72

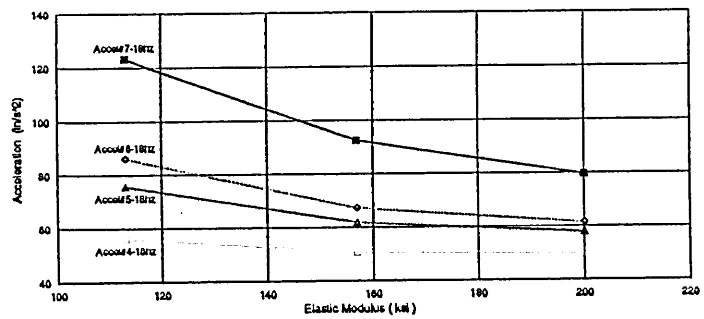
Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
18 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248

Peak Accelerations
Elastic Modulus Varied with 18 hz Input Motion



Peak Accelerations (inch / sec ^ 2)

18 hz		113	157	200	Lab	18 hz
	Accel#7-18hz	123.2	92.43	79.49	Accel#7-18hz	28.94
	Accel#6-18hz	85.88	67.23	61.48	Accel#6-18hz	32.62
	Accel#5-18hz	75.55	61.65	57.8	Accel#5-18hz	35.71
	Accel#4-18hz	56.15	50.82	49.95	Accel#4-18hz	40.02

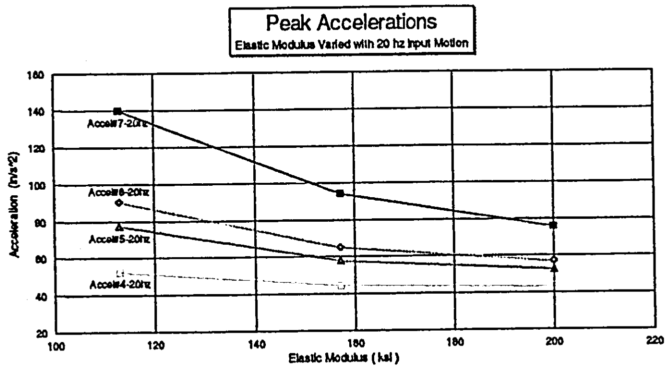
Figure 96

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
20 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

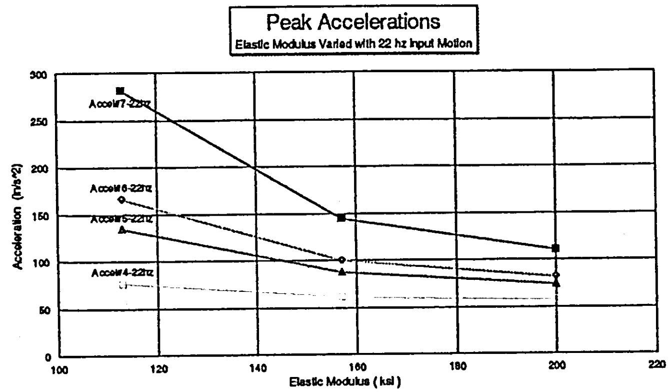
20 hz Input	Motion	113	157	200	Lab	20 hz
	Accel#7-20hz	139.80	94.03	75.55	Accel#7-20hz	65.26
	Accel#6-20hz	90.25	65.09	57.14	Accel#6-20hz	57.57
	Accel#5-20hz	77.07	57.65	52.66	Accel#5-20hz	51.1
	Accel#4-20hz	52.48	44.84	43.31	Accel#4-20hz	44.64

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
22 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

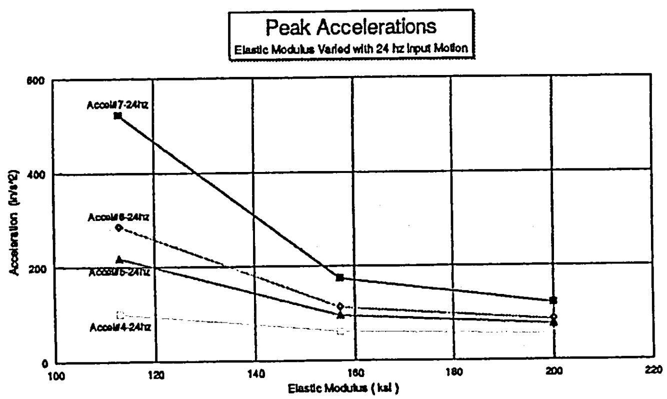
22 hz Input	Motion	113	157	200	Lab	22 hz
	Accel#7-22hz	281.60	144.20	110.20	Accel#7-22hz	65.57
	Accel#6-22hz	166.30	100.10	82.04	Accel#6-22hz	60.03
	Accel#5-22hz	134.40	87.09	73.59	Accel#5-22hz	55.72
	Accel#4-22hz	77.24	61.90	57.66	Accel#4-22hz	52.33

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
24 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

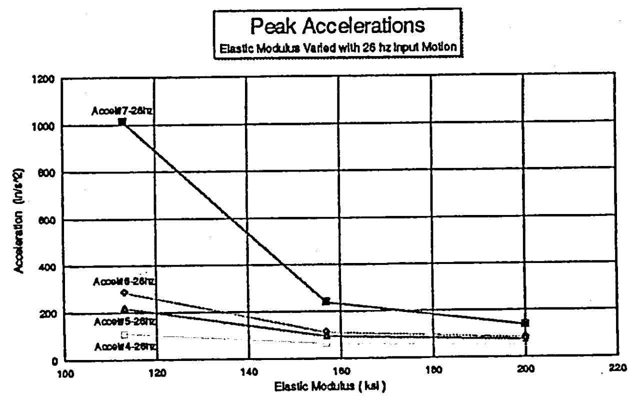
24 hz Input Motion		113	157	200	Lab	24 hz
	Accel#7-24hz	523.00	174.50	121.4	Accel#7-24hz	97.59
	Accel#6-24hz	285.30	112.60	85.59	Accel#6-24hz	79.42
	Accel#5-24hz	217.90	95.42	75.81	Accel#5-24hz	68.96
	Accel#4-24hz	100.50	62.95	56.31	Accel#4-24hz	57.88

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
26 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

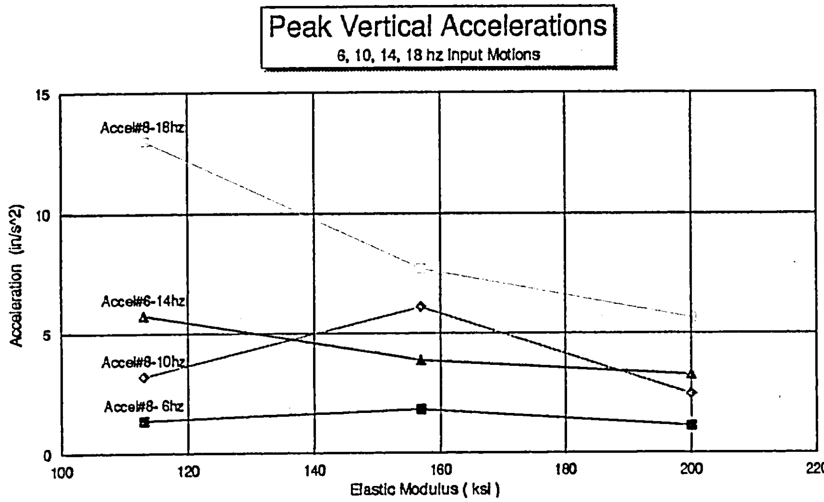
26 hz	113	157	200	Lab	26 hz
Accel#7-26hz	1013	238.6	137.9	Accel#7-26hz	97.59
Accel#6-26hz	285.3	112.6	85.59	Accel#6-26hz	79.42
Accel#5-26hz	217.9	95.42	75.81	Accel#5-26hz	68.96
Accel#4-26hz	111.4	65.02	54.3	Accel#4-26hz	57.88

Figure 97

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
6, 10, 14, 18 hz Input Frequency
Vertical Accelerations

Material Properties
E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



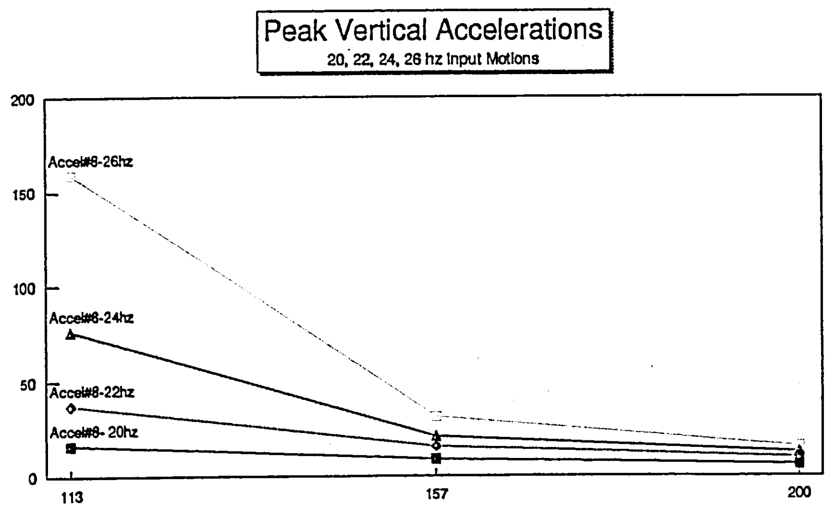
Peak Accelerations (inch / sec ^ 2)

Motion	113	157	200	Lab	
Accel#8- 6hz	1.356	1.791	1.096	Accel#8-6hz	3.694
Accel#8-10hz	3.18	6.07	2.45	Accel#8-10hz	6.773
Accel#6-14hz	5.73	3.87	3.23	Accel#6-14hz	11.08
Accel#8-18hz	12.97	7.66	5.62	Accel#8-18hz	76.96

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
20, 22, 24, 26 hz Input Frequency
Vertical Accelerations

Material Properties
E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

Motion	113	157	200	Lab	
Accel#8- 20hz	16.38	8.679	5.977	Accel#8-6hz	33.86
Accel#8-22hz	37.06	15.66	10.00	Accel#8-10hz	18.47
Accel#6-24hz	76.13	21.01	12.52	Accel#6-14hz	18.78
Accel#8-26hz	158.70	31.27	15.63	Accel#8-18hz	10.78

Figure g8

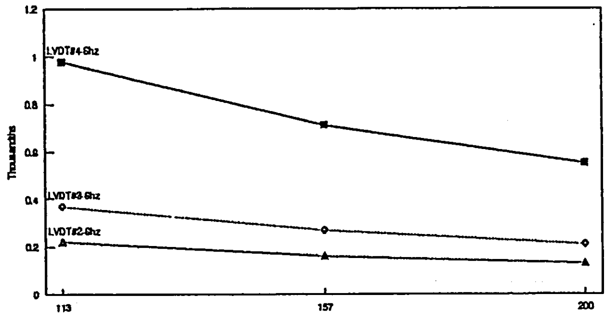
Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
6 Hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248

Peak Displacements
Elastic Modulus Varied using 6 Hz Input Motion



Peak Displacements (Inches)

6 Hz		113	157	200		LAB
	LVDT#4-6hz	9.8E-04	7.1E-04	5.5E-04	LVDT#4-6hz	3.7E-02
	LVDT#3-6hz	3.7E-04	2.7E-04	2.1E-04	LVDT#3-6hz	3.7E-02
	LVDT#2-6hz	2.2E-04	1.6E-04	1.3E-04	LVDT#2-6hz	3.7E-02

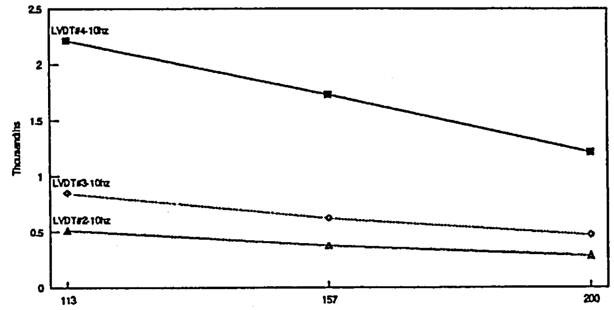
Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
10 Hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248

Peak Displacements
Elastic Modulus Varied using 10 Hz Input Motion



Peak Displacements (Inches)

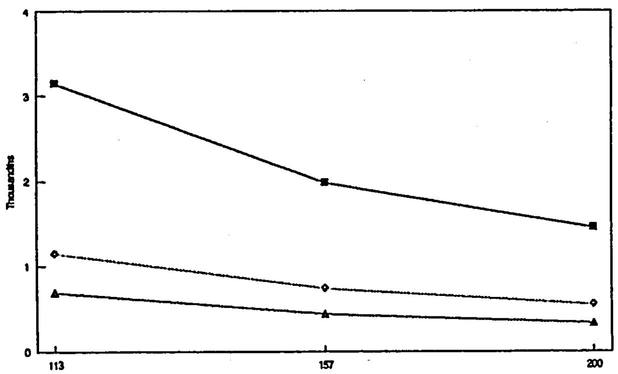
10 Hz		113	157	200		LAB
	LVDT#4-10hz	2.2E-03	1.7E-03	1.2E-03	LVDT#4-10hz	1.3E-03
	LVDT#3-10hz	8.4E-04	6.2E-04	4.7E-04	LVDT#3-10hz	6.6E-04
	LVDT#2-10hz	5.1E-04	3.7E-04	2.8E-04	LVDT#2-10hz	1.6E-02

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
14 Hz Input Motion

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (Inches)

		113	157	200		LAB
	LVDT#4-14hz	3.1E-03	2.0E-03	1.5E-03	LVDT#4-14hz	1.2E-03
	LVDT#3-14hz	1.2E-03	7.4E-04	5.5E-04	LVDT#3-14hz	6.2E-04
	LVDT#2-14hz	6.9E-04	4.4E-04	3.3E-04	LVDT#2-14hz	1.1E-02

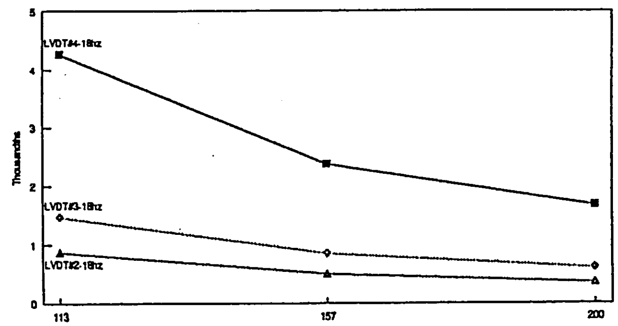
Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
18 Hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248

Peak Displacements
Elastic Modulus Varied using 18 Hz Input Motion



Peak Displacements (Inches)

		113	157	200		LAB
	LVDT#4-18hz	4.3E-03	2.4E-03	1.7E-03	LVDT#4-18hz	1.9E-03
	LVDT#3-18hz	1.5E-03	8.6E-04	6.2E-04	LVDT#3-18hz	1.2E-03
	LVDT#2-18hz	8.7E-04	5.1E-04	3.7E-04	LVDT#2-18hz	6.2E-03

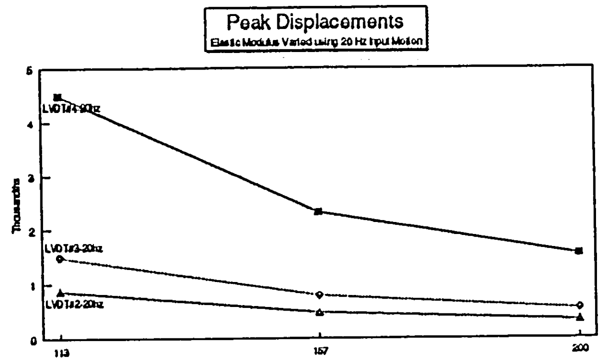
Figure 99

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
20 Hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (Inches)

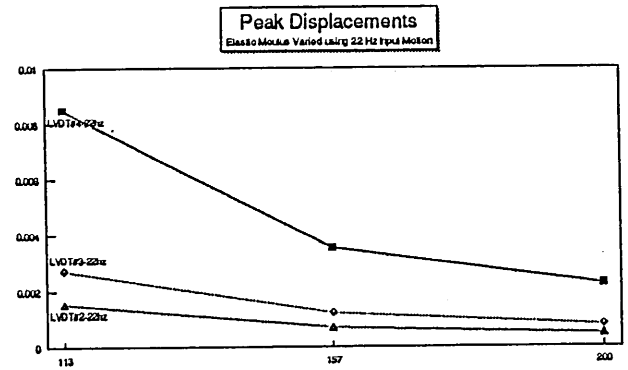
20 Hz		113	157	200		LAB
	LVDT#4-20hz	4.5E-03	2.3E-03	1.6E-03	LVDT#4-20hz	1.7E-03
	LVDT#3-20hz	1.5E-03	8.0E-04	5.5E-04	LVDT#3-20hz	1.2E-03
	LVDT#2-20hz	8.7E-04	4.8E-04	3.4E-04	LVDT#2-20hz	5.5E-03

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
22 Hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (Inches)

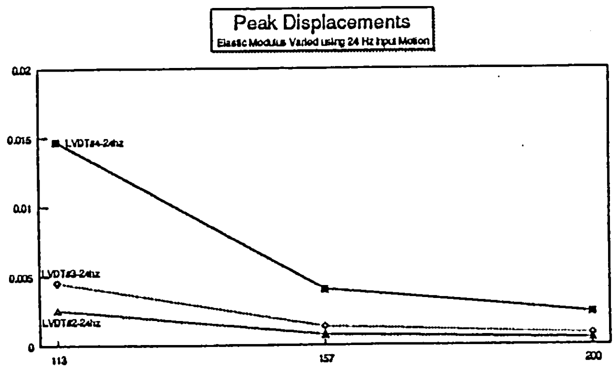
22 Hz		113	157	200		LAB
	LVDT#4-22hz	8.5E-03	3.6E-03	2.3E-03	LVDT#4-22hz	9.7E-04
	LVDT#3-22hz	2.7E-03	1.2E-03	8.1E-04	LVDT#3-22hz	8.1E-04
	LVDT#2-22hz	1.6E-03	7.2E-04	4.7E-04	LVDT#2-22hz	5.6E-03

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
24 Hz Input Motion

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (Inches)

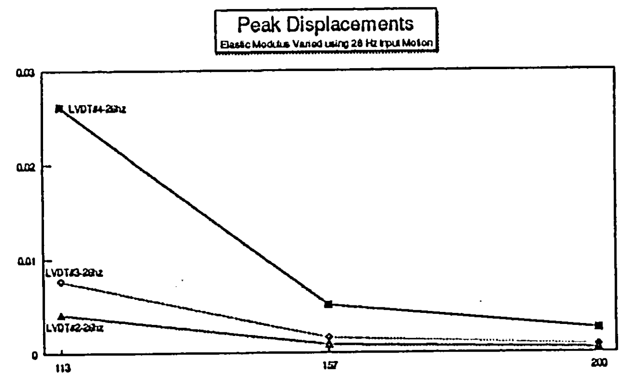
24 Hz		113	157	200		LAB
	LVDT#4-24hz	1.5E-02	4.1E-03	2.4E-03	LVDT#4-24hz	2.0E-03
	LVDT#3-24hz	4.5E-03	1.4E-03	8.4E-04	LVDT#3-24hz	1.1E-03
	LVDT#2-24hz	2.5E-03	7.8E-04	4.9E-04	LVDT#2-24hz	4.8E-03

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
26 Hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

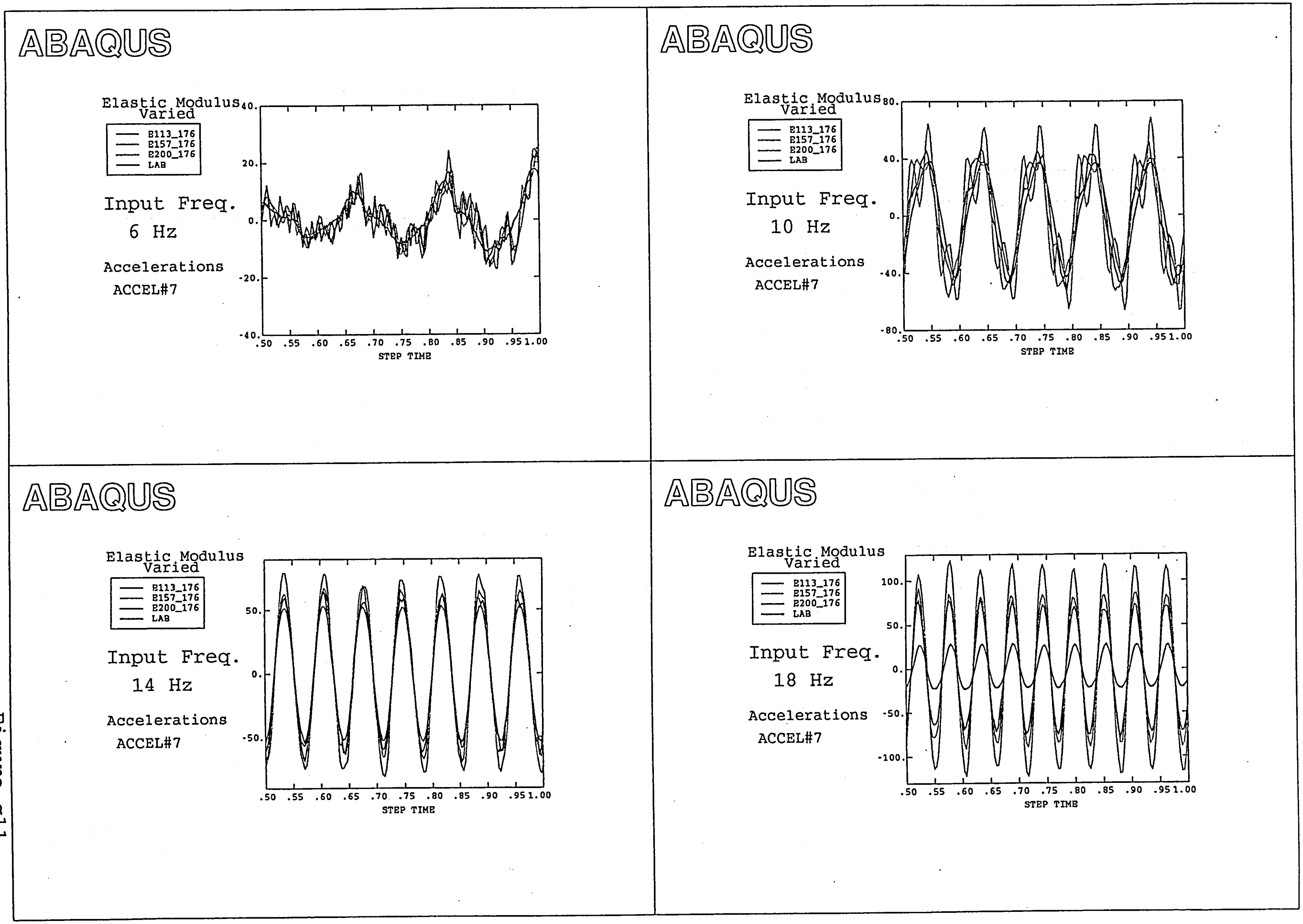
Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (Inches)

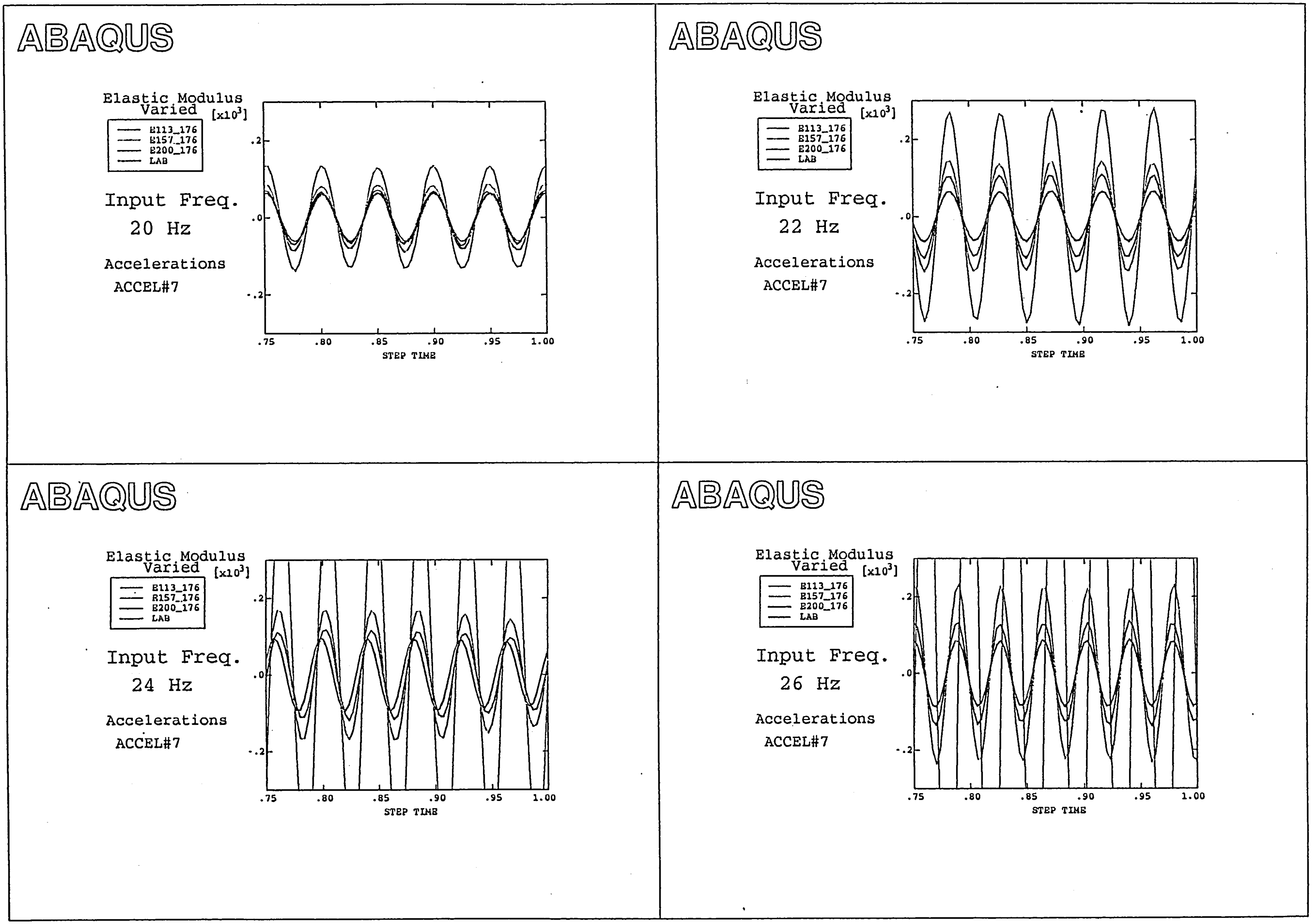
26 Hz		113	157	200		LAB
	LVDT#4-26hz	2.6E-02	5.1E-03	2.6E-03	LVDT#4-26hz	1.5E-03
	LVDT#3-26hz	7.6E-03	1.6E-03	8.7E-04	LVDT#3-26hz	1.1E-03
	LVDT#2-26hz	4.1E-03	9.3E-04	5.0E-04	LVDT#2-26hz	3.5E-03

Figure g10



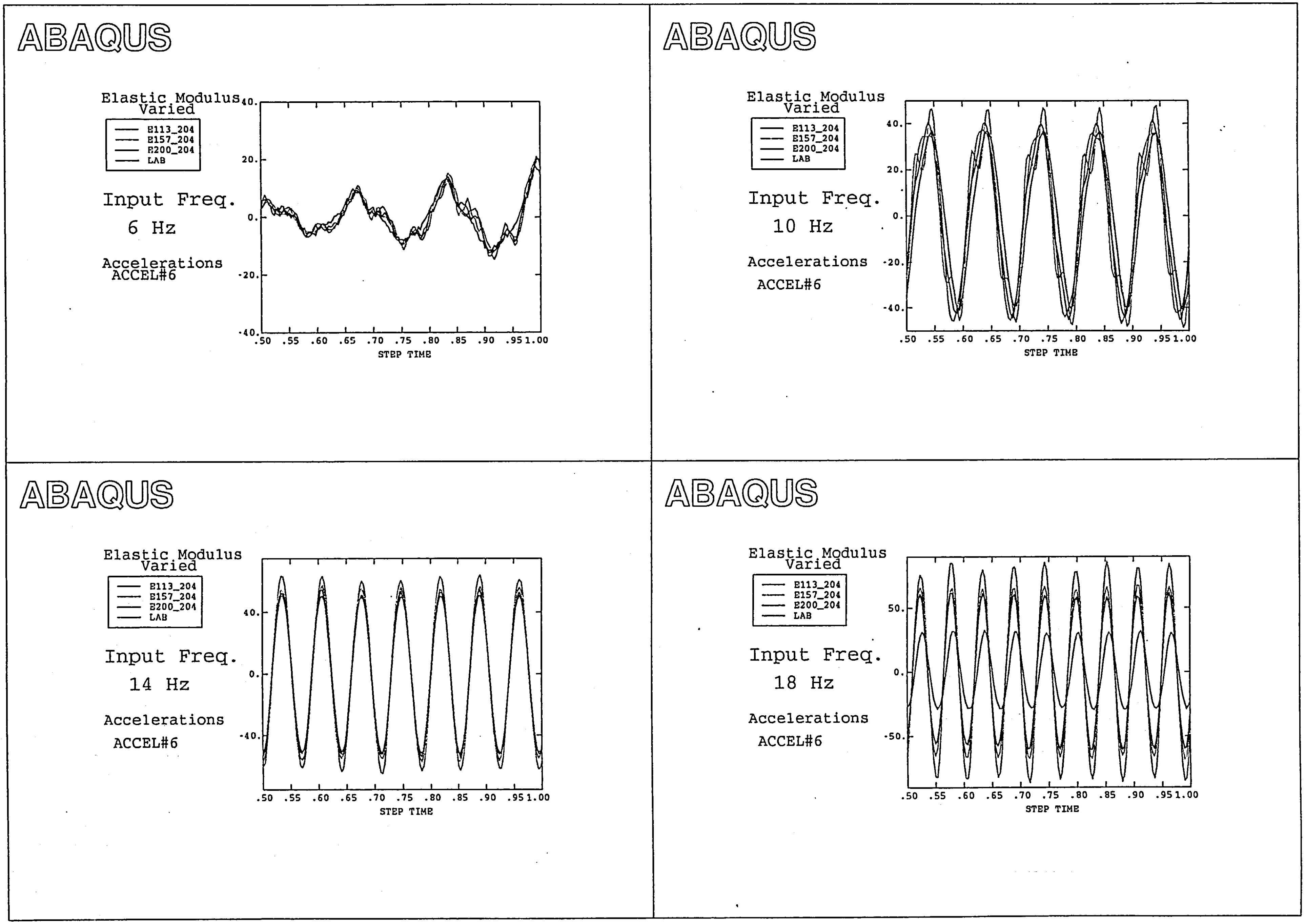
ABAQUS
Elastic Modulus Varied
E113_176
E157_176
E200_176
LAB
Input Freq.
6 Hz
Accelerations
ACCEL#7
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_176
E157_176
E200_176
LAB
Input Freq.
10 Hz
Accelerations
ACCEL#7
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_176
E157_176
E200_176
LAB
Input Freq.
14 Hz
Accelerations
ACCEL#7
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_176
E157_176
E200_176
LAB
Input Freq.
18 Hz
Accelerations
ACCEL#7
STEP TIME

Figure 911



ABAQUS
Elastic Modulus Varied
B113_176
B157_176
B200_176
LAB
Input Freq. 20 Hz
Accelerations ACCEL#7
[x10^3]
.2
.0
-.2
.75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
B113_176
B157_176
B200_176
LAB
Input Freq. 22 Hz
Accelerations ACCEL#7
[x10^3]
.2
.0
-.2
.75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
B113_176
B157_176
B200_176
LAB
Input Freq. 24 Hz
Accelerations ACCEL#7
[x10^3]
.2
.0
-.2
.75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
B113_176
B157_176
B200_176
LAB
Input Freq. 26 Hz
Accelerations ACCEL#7
[x10^3]
.2
.0
-.2
.75 .80 .85 .90 .95 1.00
STEP TIME

Figure 912



ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq. 6 Hz
Accelerations ACCEL#6
40.
20.
0.
-20.
-40.
.50 .55 .60 .65 .70 .75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq. 10 Hz
Accelerations ACCEL#6
40.
20.
0.
-20.
-40.
.50 .55 .60 .65 .70 .75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq. 14 Hz
Accelerations ACCEL#6
40.
0.
-40.
.50 .55 .60 .65 .70 .75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq. 18 Hz
Accelerations ACCEL#6
50.
0.
-50.
.50 .55 .60 .65 .70 .75 .80 .85 .90 .95 1.00
STEP TIME

Figure 913

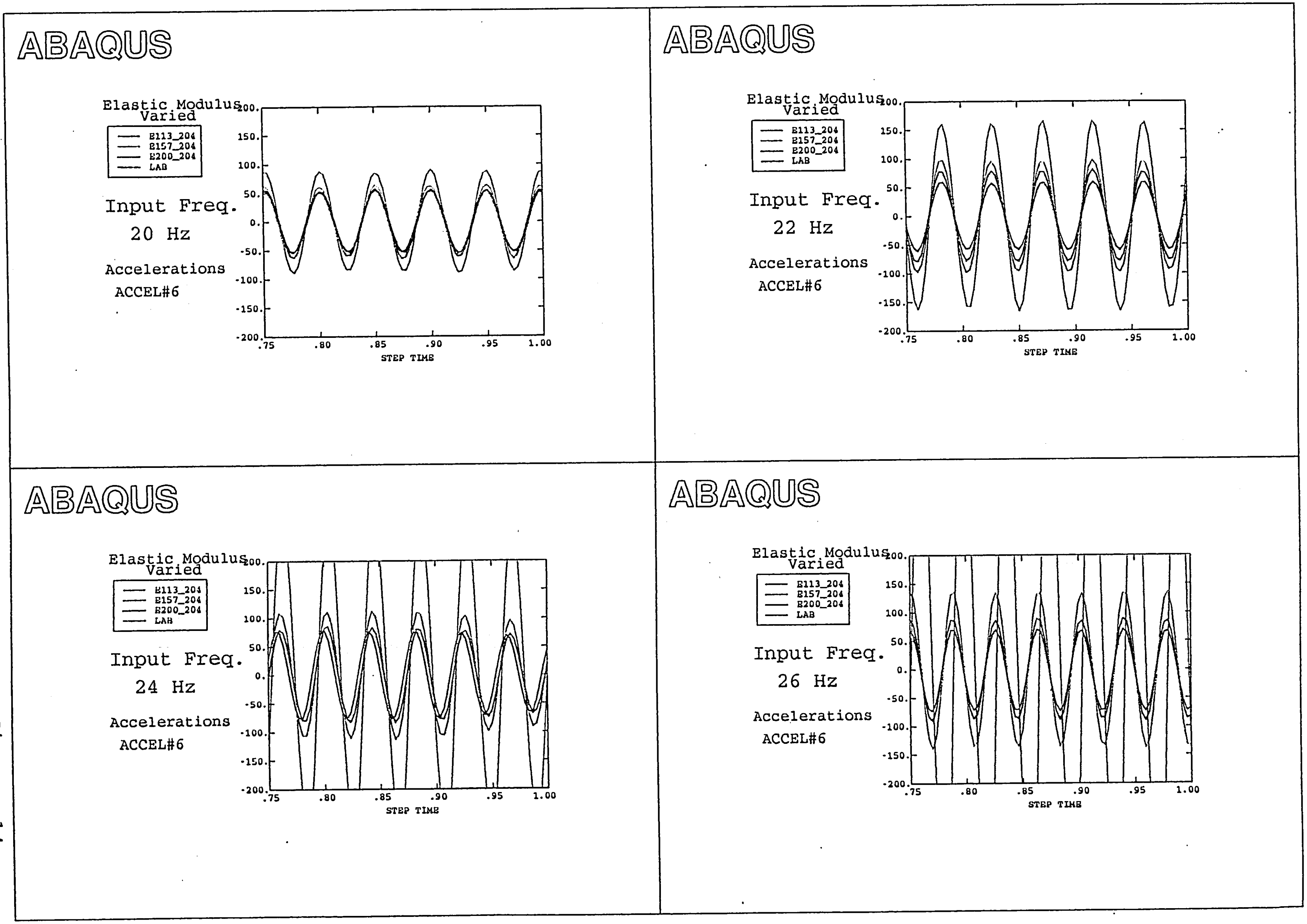

ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq.
20 Hz
Accelerations
ACCEL#6
200. 150. 100. 50. 0. -50. -100. -150. -200.
.75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq.
22 Hz
Accelerations
ACCEL#6
200. 150. 100. 50. 0. -50. -100. -150. -200.
.75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq.
24 Hz
Accelerations
ACCEL#6
200. 150. 100. 50. 0. -50. -100. -150. -200.
.75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq.
26 Hz
Accelerations
ACCEL#6
200. 150. 100. 50. 0. -50. -100. -150. -200.
.75 .80 .85 .90 .95 1.00
STEP TIME

Figure 914

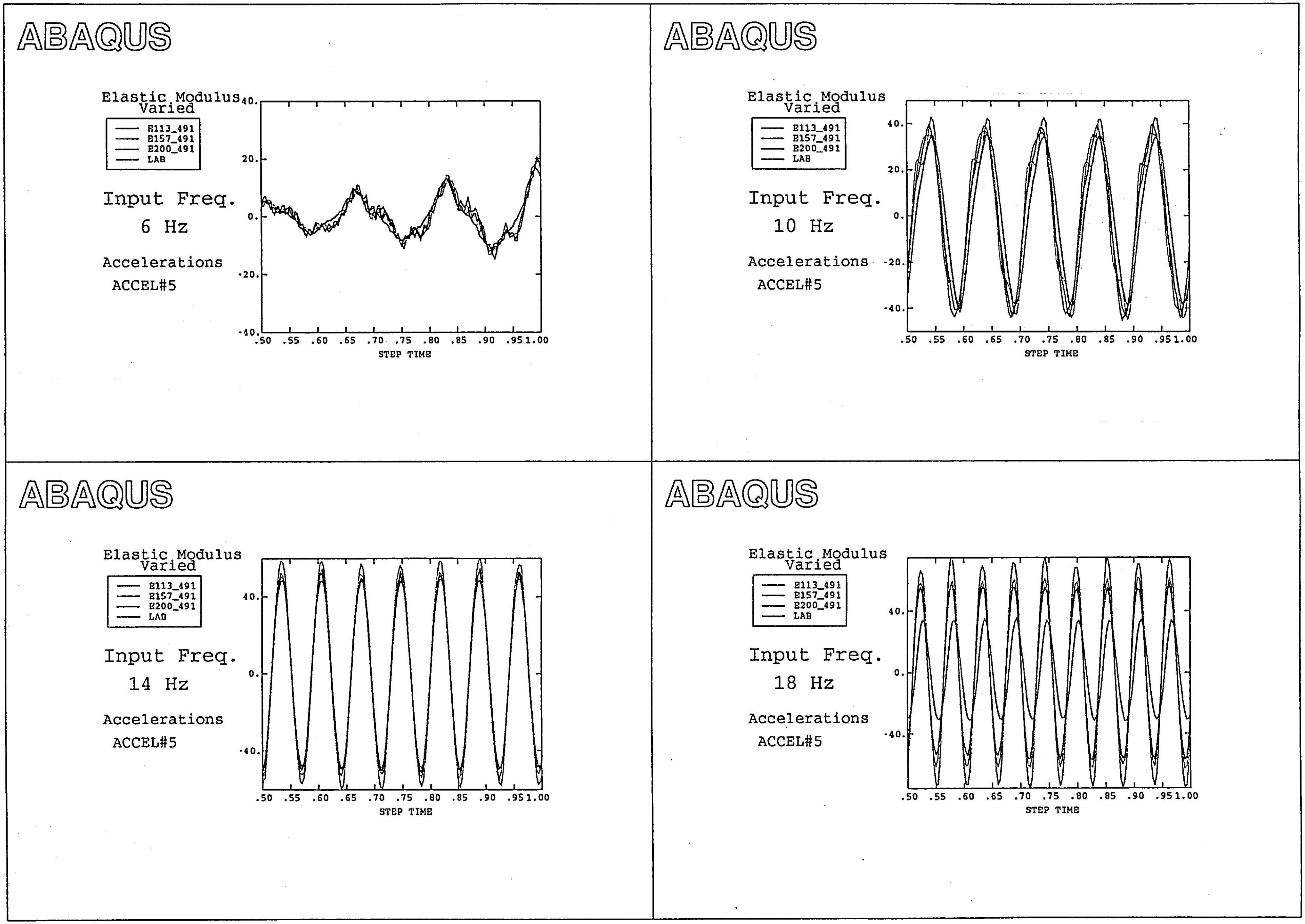

ABAQUS
Elastic Modulus Varied
E113_491
E157_491
E200_491
LAB
Input Freq.
6 Hz
Accelerations
ACCEL#5
40.
20.
0.
-20.
-40.
.50 .55 .60 .65 .70 .75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_491
E157_491
E200_491
LAB
Input Freq.
10 Hz
Accelerations
ACCEL#5
40.
20.
0.
-20.
-40.
.50 .55 .60 .65 .70 .75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_491
E157_491
E200_491
LAB
Input Freq.
14 Hz
Accelerations
ACCEL#5
40.
0.
-40.
.50 .55 .60 .65 .70 .75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_491
E157_491
E200_491
LAB
Input Freq.
18 Hz
Accelerations
ACCEL#5
40.
0.
-40.
.50 .55 .60 .65 .70 .75 .80 .85 .90 .95 1.00
STEP TIME

Figure g15

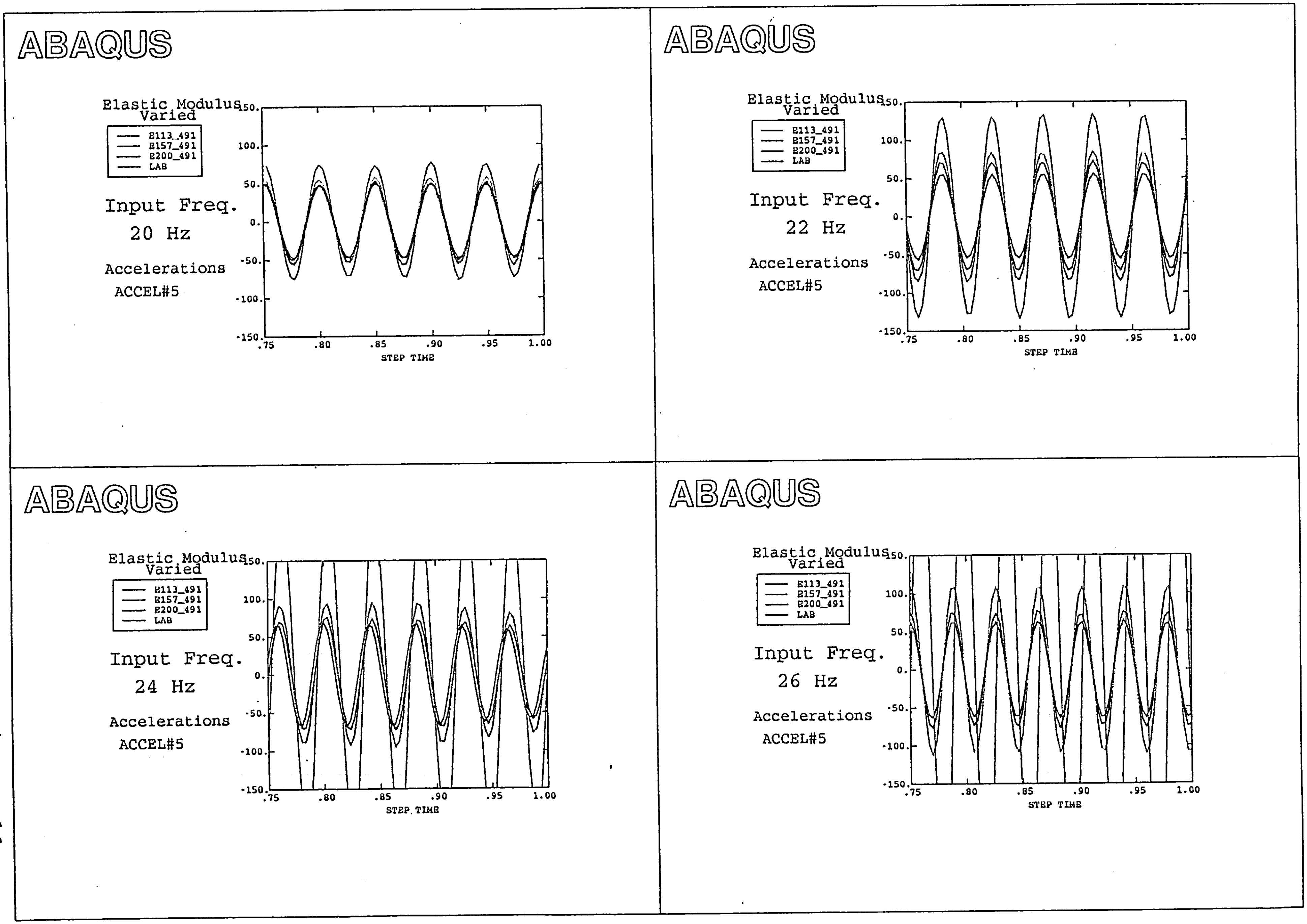

ABAQUS
Elastic Modulus Varied
E113_491
E157_491
E200_491
LAB
Input Freq.
20 Hz
Accelerations
ACCEL#5
150.
100.
50.
0.
-50.
-100.
-150.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_491
E157_491
E200_491
LAB
Input Freq.
22 Hz
Accelerations
ACCEL#5
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_491
E157_491
E200_491
LAB
Input Freq.
24 Hz
Accelerations
ACCEL#5
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_491
E157_491
E200_491
LAB
Input Freq.
26 Hz
Accelerations
ACCEL#5
STEP TIME

Figure 916

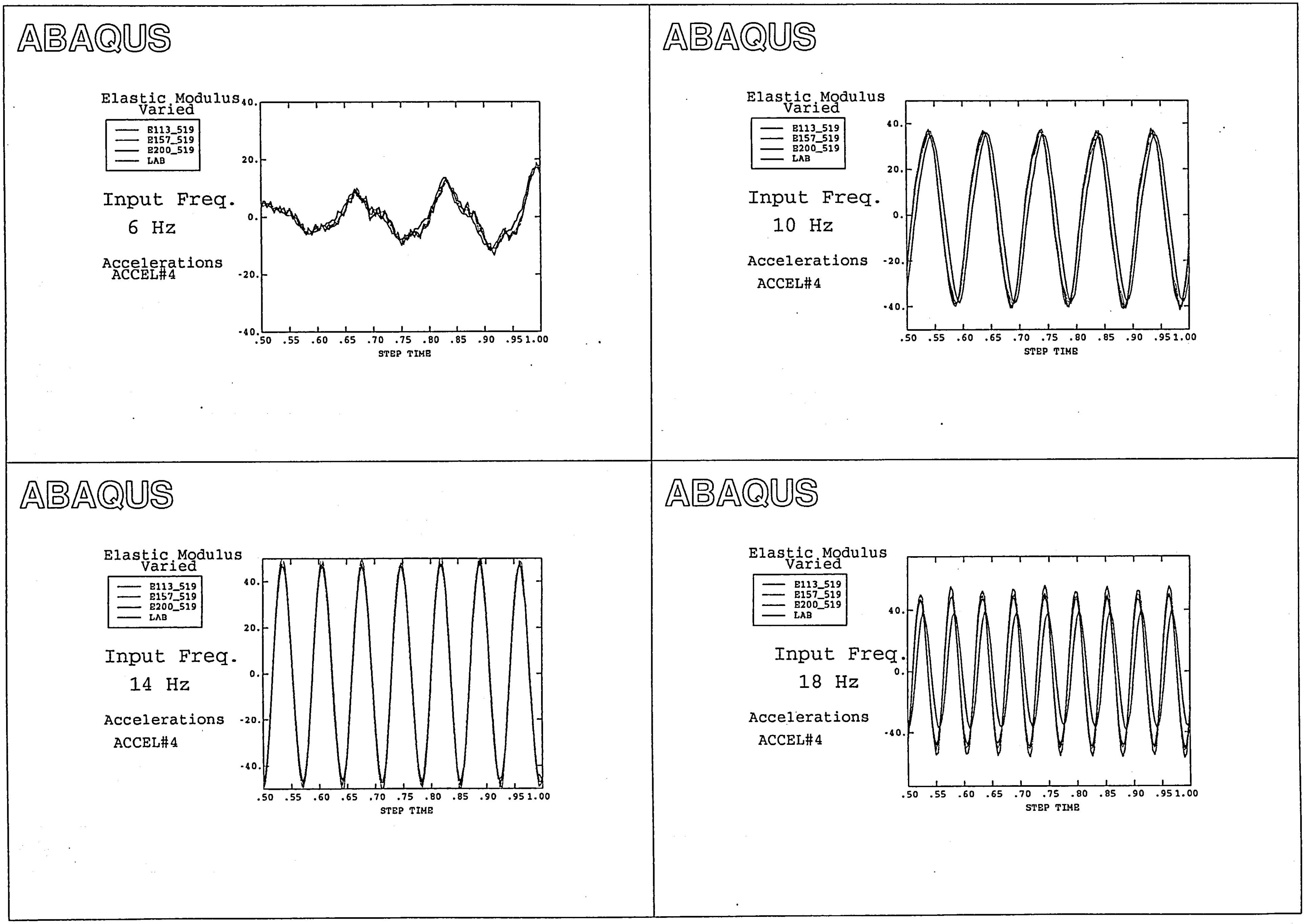

ABAQUS
Elastic Modulus Varied
E113_519
E157_519
E200_519
LAB
Input Freq. 6 Hz
Accelerations ACCEL#4
40.
20.
0.
-20.
-40.
.50 .55 .60 .65 .70 .75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_519
E157_519
E200_519
LAB
Input Freq. 10 Hz
Accelerations ACCEL#4
40.
20.
0.
-20.
-40.
.50 .55 .60 .65 .70 .75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_519
E157_519
E200_519
LAB
Input Freq. 14 Hz
Accelerations ACCEL#4
40.
20.
0.
-20.
-40.
.50 .55 .60 .65 .70 .75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_519
E157_519
E200_519
LAB
Input Freq. 18 Hz
Accelerations ACCEL#4
40.
0.
-40.
.50 .55 .60 .65 .70 .75 .80 .85 .90 .95 1.00
STEP TIME

Figure g17

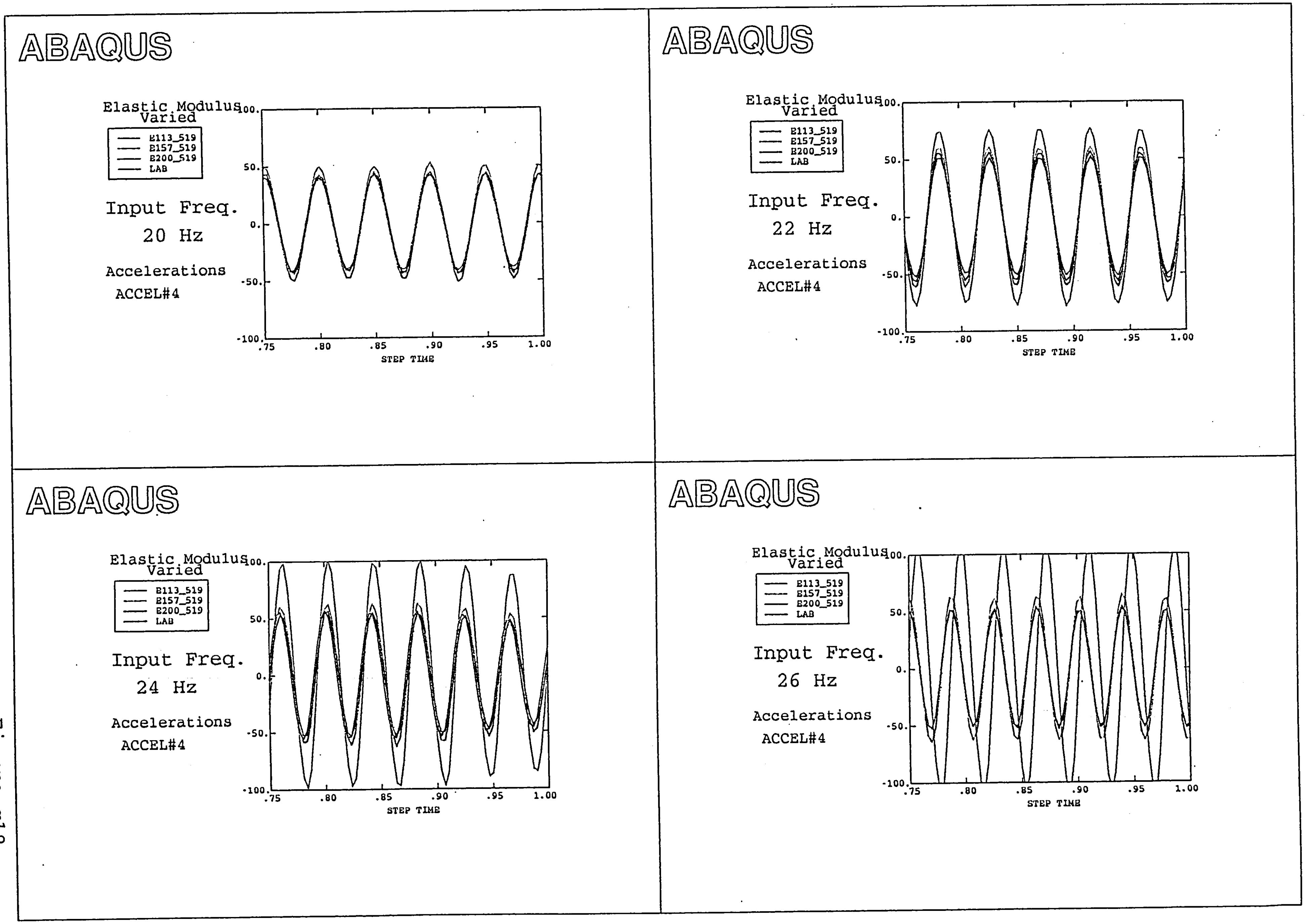

ABAQUS
Elastic Modulus Varied
B113_519
B157_519
B200_519
LAB
Input Freq. 20 Hz
Accelerations ACCEL#4
STEP TIME
ABAQUS
Elastic Modulus Varied
B113_519
B157_519
B200_519
LAB
Input Freq. 22 Hz
Accelerations ACCEL#4
STEP TIME
ABAQUS
Elastic Modulus Varied
B113_519
B157_519
B200_519
LAB
Input Freq. 24 Hz
Accelerations ACCEL#4
STEP TIME
ABAQUS
Elastic Modulus Varied
B113_519
B157_519
B200_519
LAB
Input Freq. 26 Hz
Accelerations ACCEL#4
STEP TIME

Figure 918

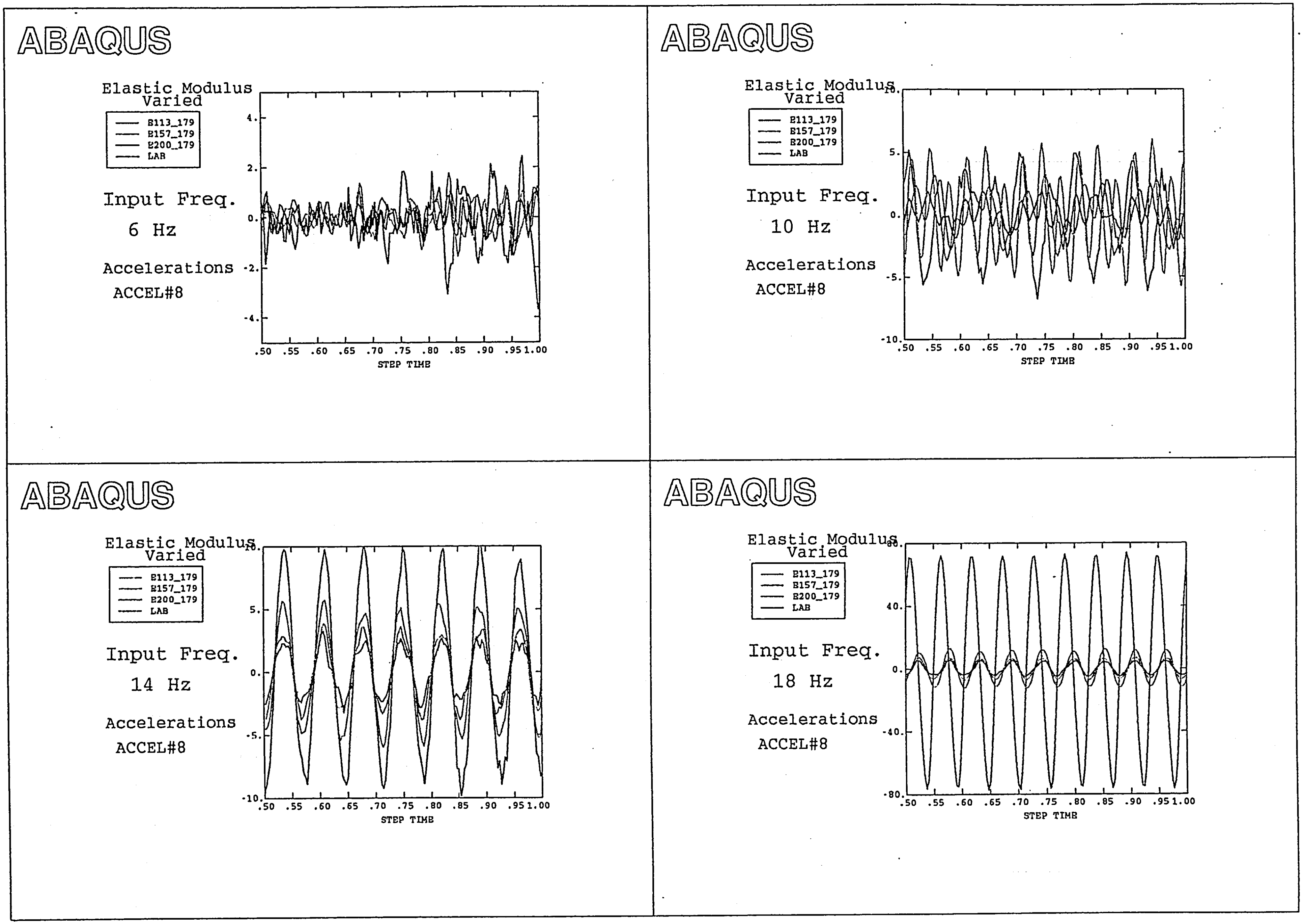

ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq. 6 Hz
Accelerations ACCEL#8
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq. 10 Hz
Accelerations ACCEL#8
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq. 14 Hz
Accelerations ACCEL#8
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq. 18 Hz
Accelerations ACCEL#8
STEP TIME

Figure 919

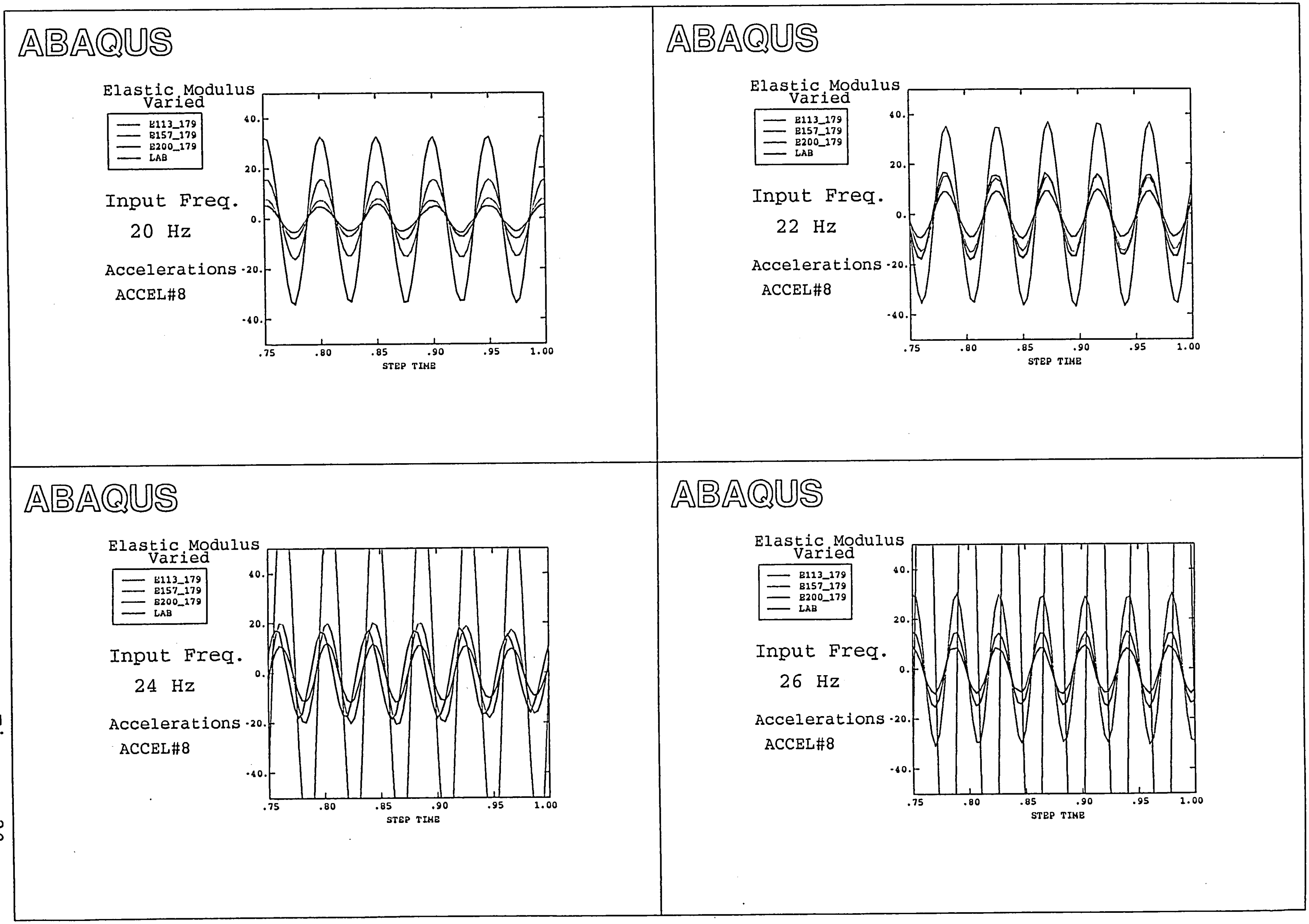

ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq. 20 Hz
Accelerations ACCEL#8
40.
20.
0.
-20.
-40.
.75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq. 22 Hz
Accelerations ACCEL#8
40.
20.
0.
-20.
-40.
.75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq. 24 Hz
Accelerations ACCEL#8
40.
20.
0.
-20.
-40.
.75 .80 .85 .90 .95 1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq. 26 Hz
Accelerations ACCEL#8
40.
20.
0.
-20.
-40.
.75 .80 .85 .90 .95 1.00
STEP TIME

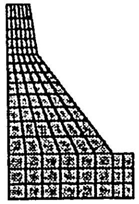
Figure 920

ABAQUS

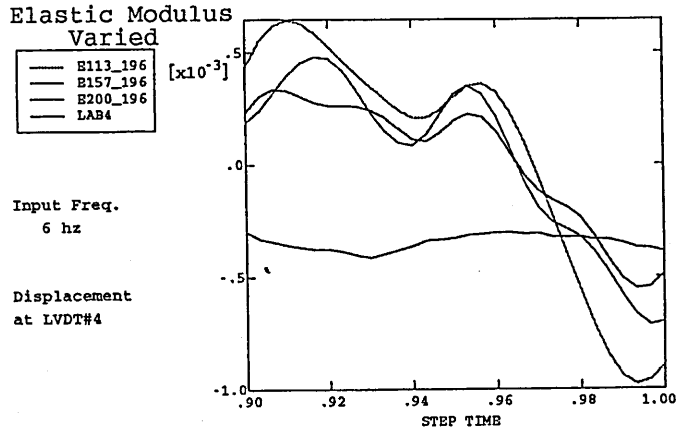
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus

At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis

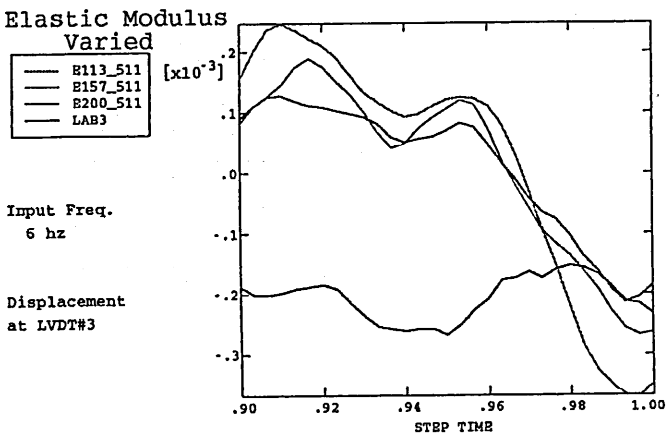
Input Record SHAKEA
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

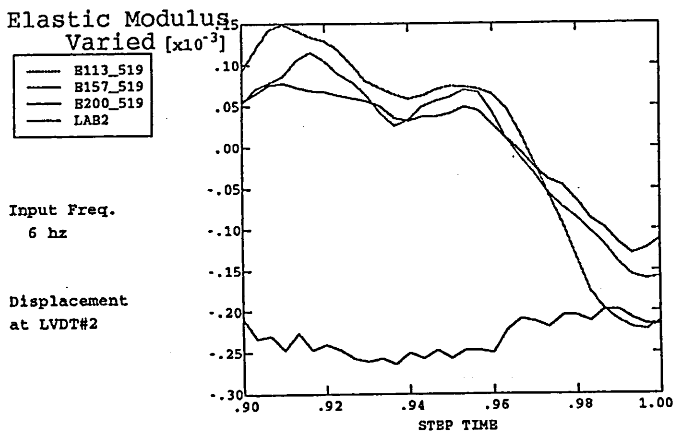


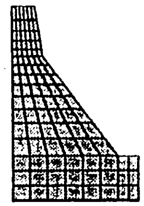
Figure 921

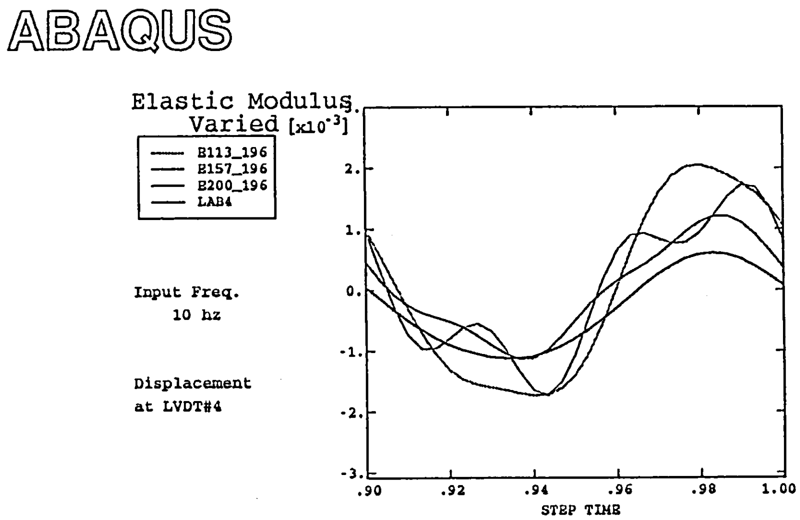
ABAQUS

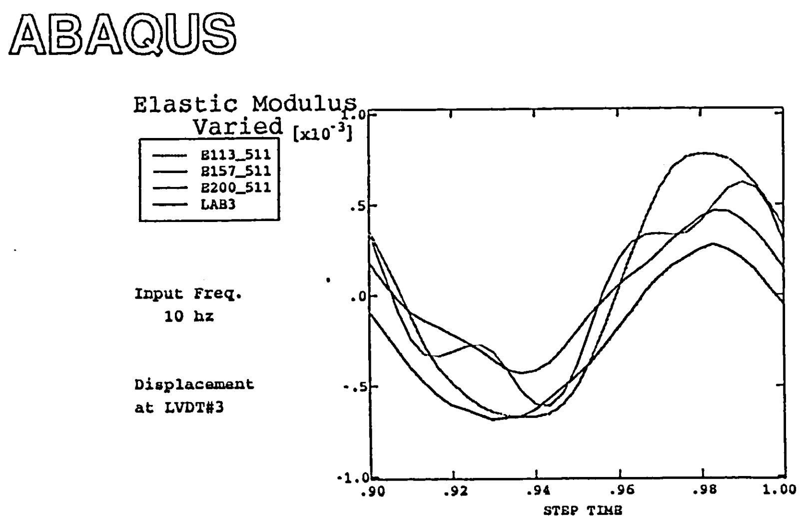
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus

At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis

Input Record SHAKEA
Mesh # 3







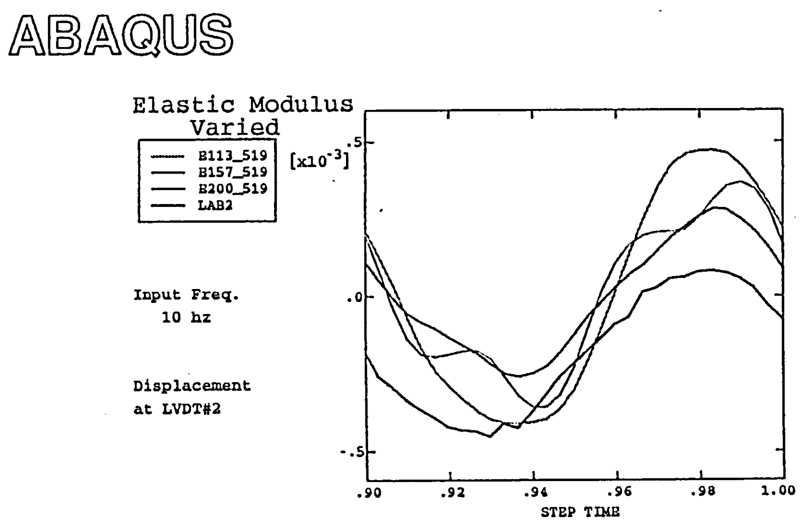


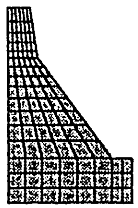
Figure 922

ABAQUS

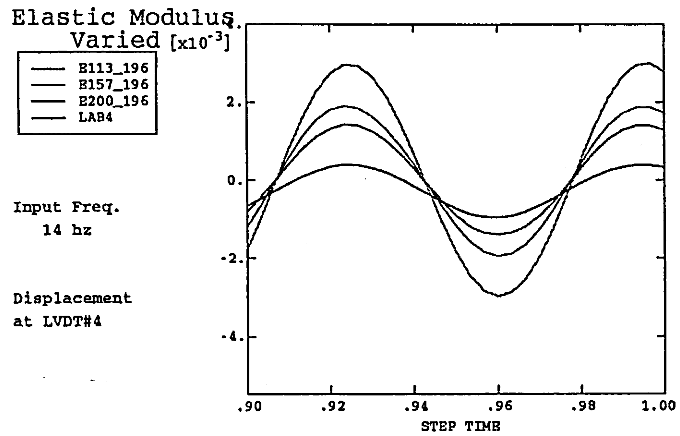
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus

At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis

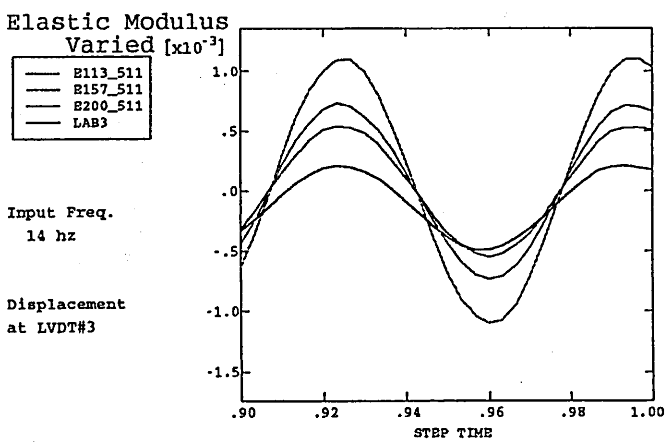
Input Record SHAKEA
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

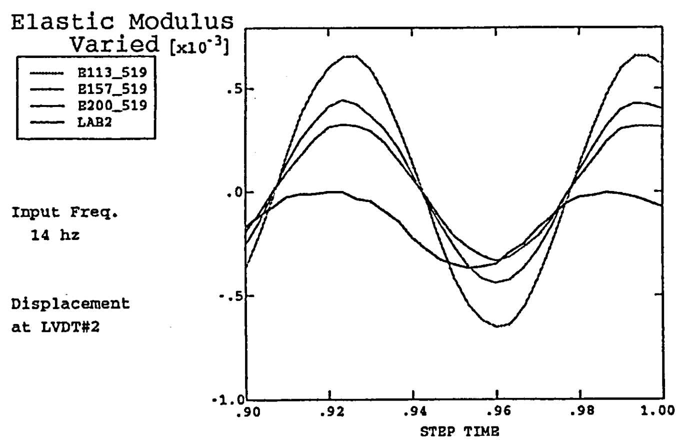


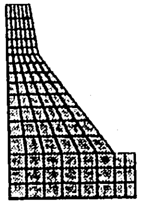
Figure 923

ABAQUS

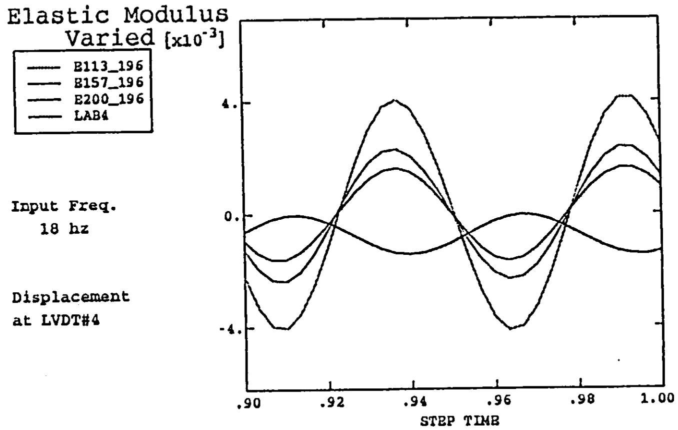
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus

At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis

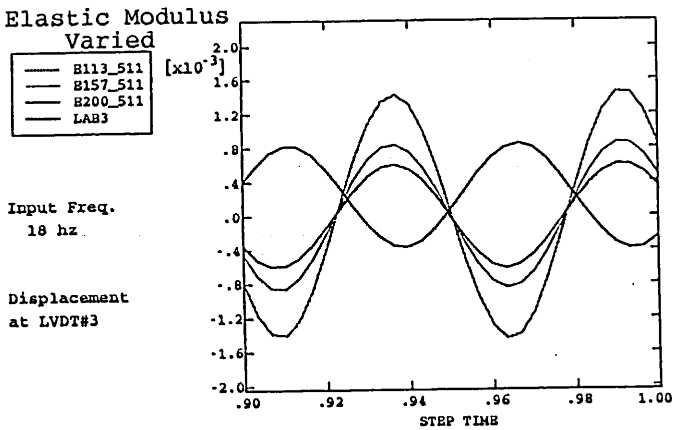
Input Record SHAKEA
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

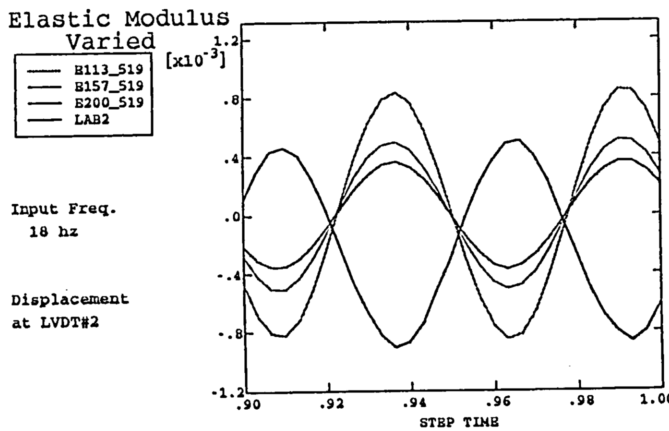


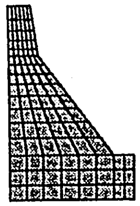
Figure g24

ABAQUS

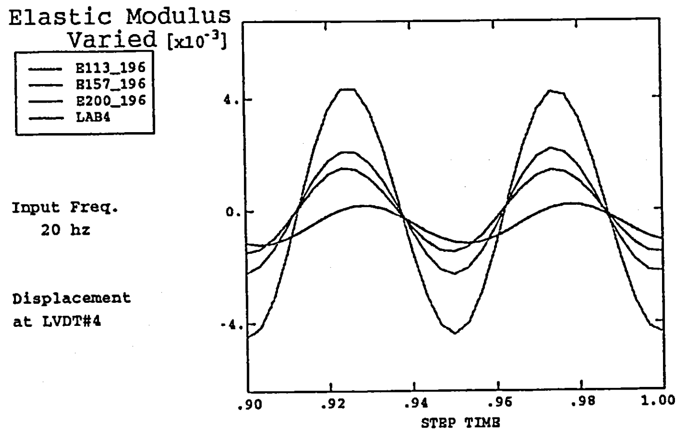
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus

At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis

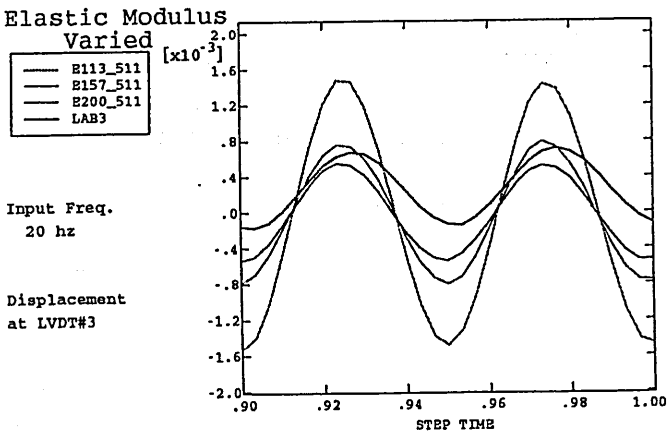
Input Record SHAKEA
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

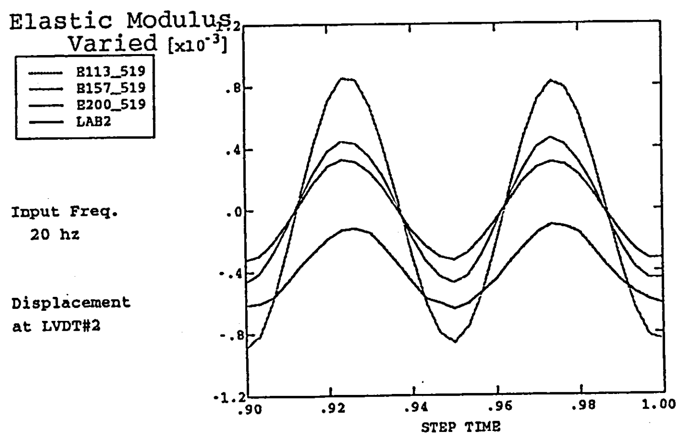


Figure 925

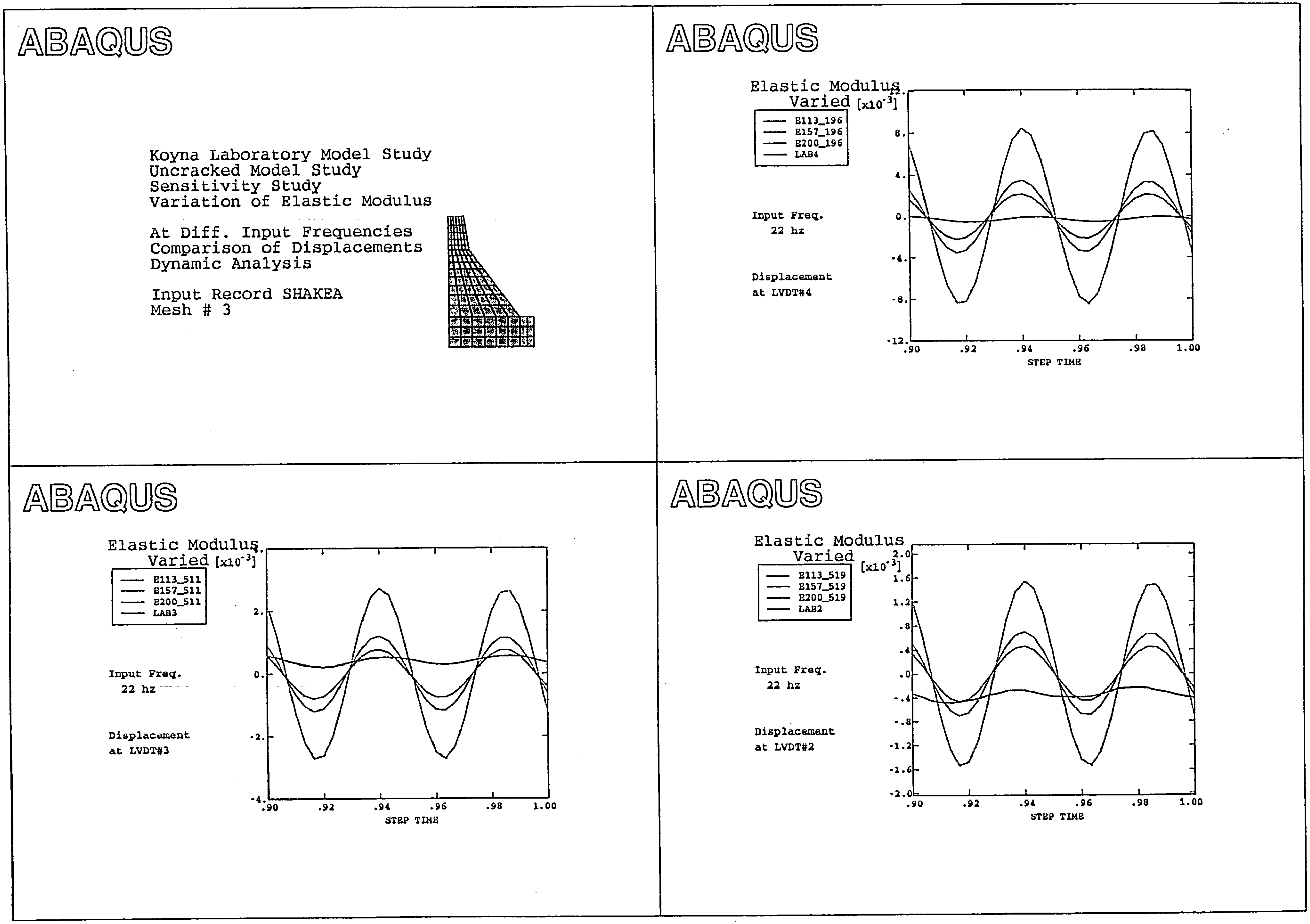

ABAQUS
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus
At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis
Input Record SHAKEA
Mesh # 3
ABAQUS
Elastic Modulus Varied
[x10^-3]
E113_196
E157_196
E200_196
LAB4
Input Freq. 22 hz
Displacement at LVDT#4
12.
8.
4.
0.
-4.
-8.
-12.
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
[x10^-3]
E113_511
E157_511
E200_511
LAB3
Input Freq. 22 hz
Displacement at LVDT#3
4.
2.
0.
-2.
-4.
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
[x10^-3]
E113_519
E157_519
E200_519
LAB2
Input Freq. 22 hz
Displacement at LVDT#2
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
.90
.92
.94
.96
.98
1.00
STEP TIME

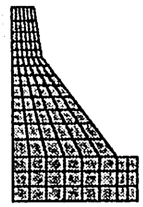
Figure g26

ABAQUS

Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus

At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis

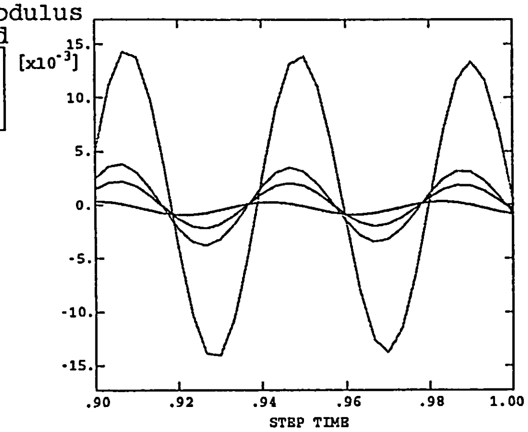
Input Record SHAKEA
Mesh # 3



ABAQUS

Elastic Modulus
Varied

B113_196
B157_196
B200_196
LAB4



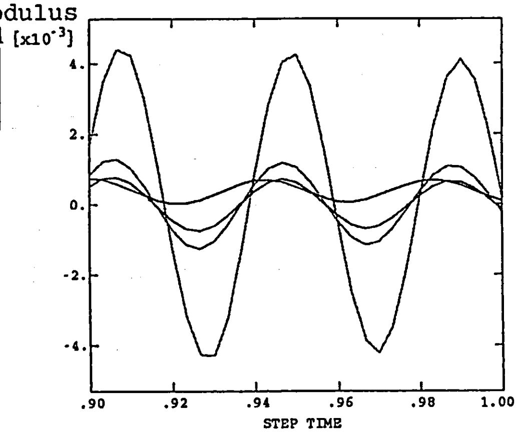
Input Freq.
24 hz

Displacement
at LVDT#4

ABAQUS

Elastic Modulus
Varied [x10^-3]

B113_511
B157_511
B200_511
LAB3



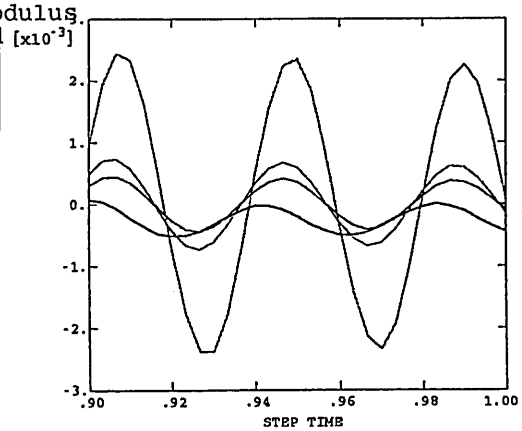
Input Freq.
24 hz

Displacement
at LVDT#3

ABAQUS

Elastic Modulus
Varied [x10^-3]

B113_519
B157_519
B200_519
LAB2



Input Freq.
24 hz

Displacement
at LVDT#2

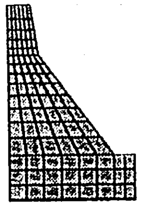
Figure 927

ABAQUS

Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus

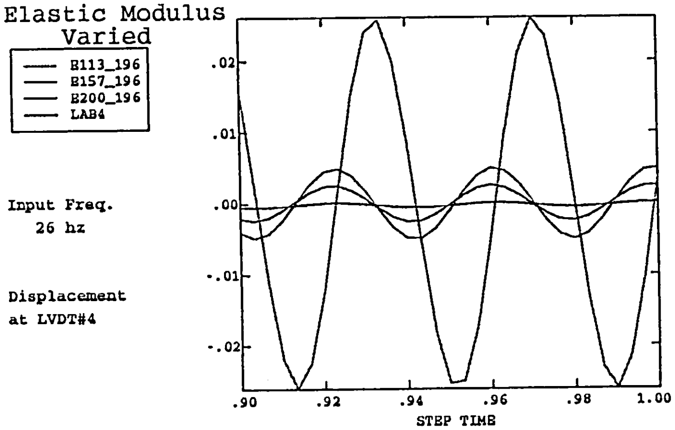
At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis

Input Record SHAKEA
Mesh # 3



ABAQUS

Elastic Modulus
Varied

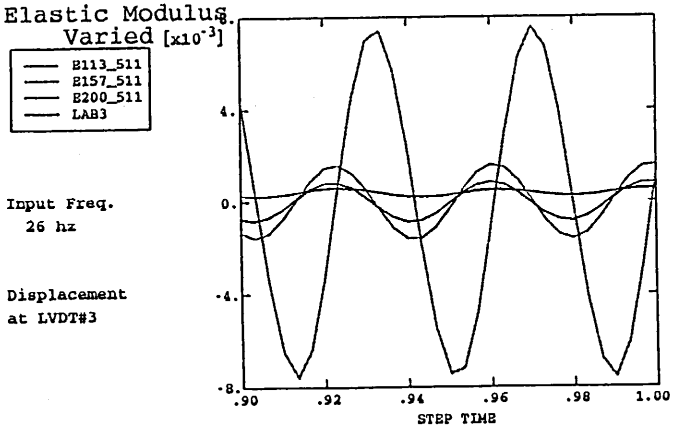


Input Freq.
26 hz

Displacement
at LVDT#4

ABAQUS

Elastic Modulus
Varied

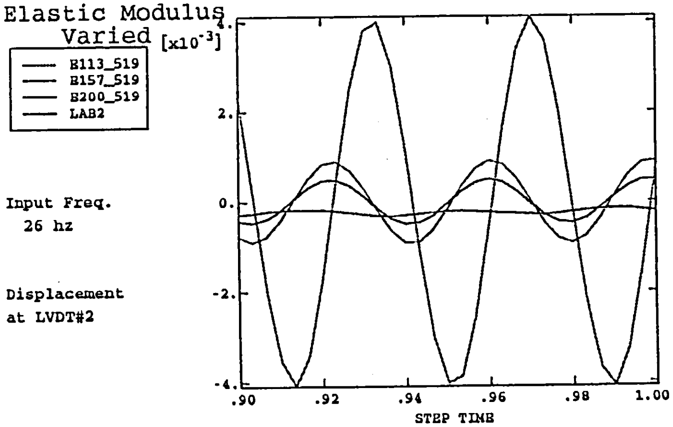


Input Freq.
26 hz

Displacement
at LVDT#3

ABAQUS

Elastic Modulus
Varied



Input Freq.
26 hz

Displacement
at LVDT#2

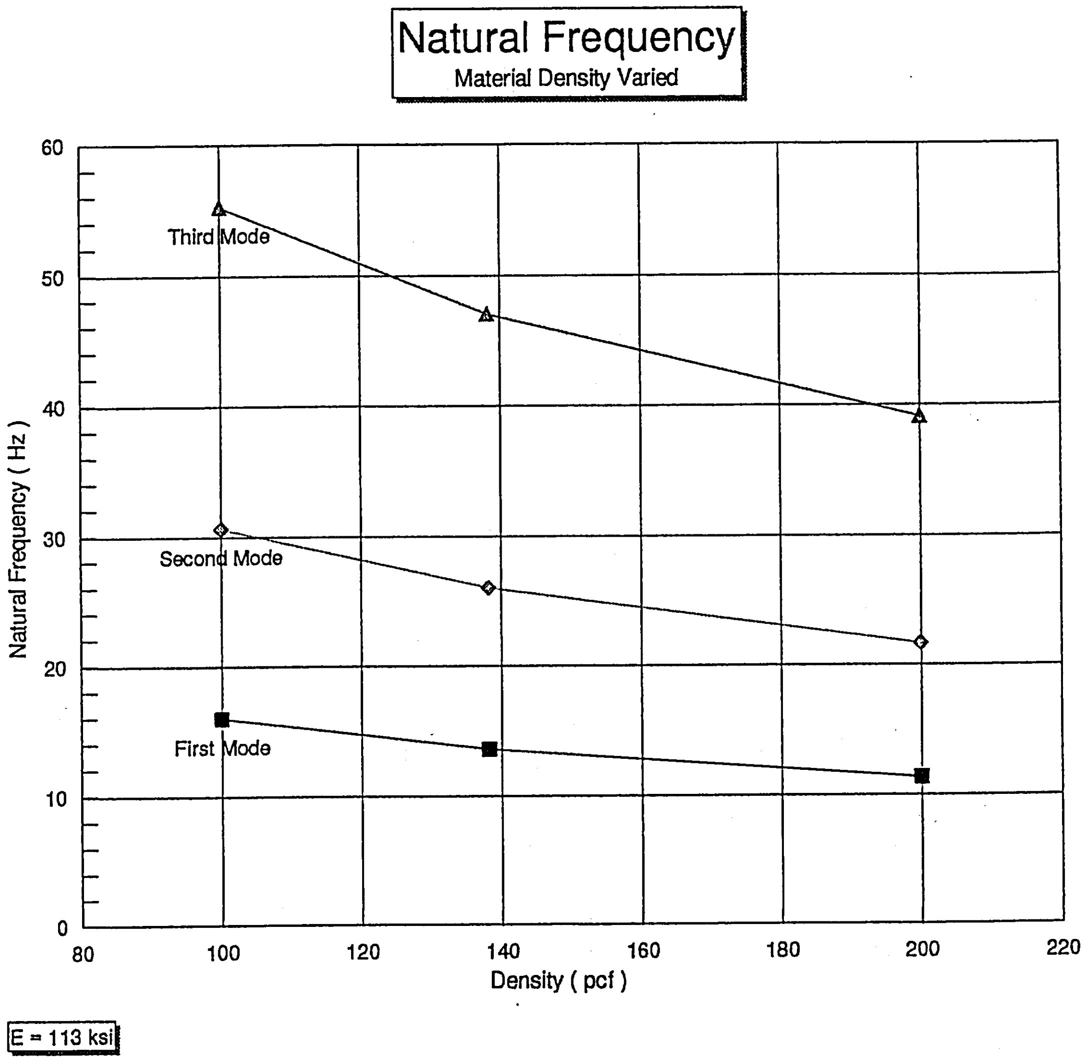
Figure 928

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

Elastic Modulus = 113 ksi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Natural Frequencies (Hz)				
Mode	100	138.2	200	LAB
1	16.0	13.6	11.3	18.0
2	30.6	26.0	21.6	24.0
3	55.3	47.0	39.1	30.0
4	65.8	55.9	46.5	
5	68.7	58.4	48.5	
6	70.8	60.2	50.1	
7	75.2	64.0	53.2	
8	76.2	64.8	53.9	
9	76.9	65.4	54.4	
10	78.4	66.7	55.4	

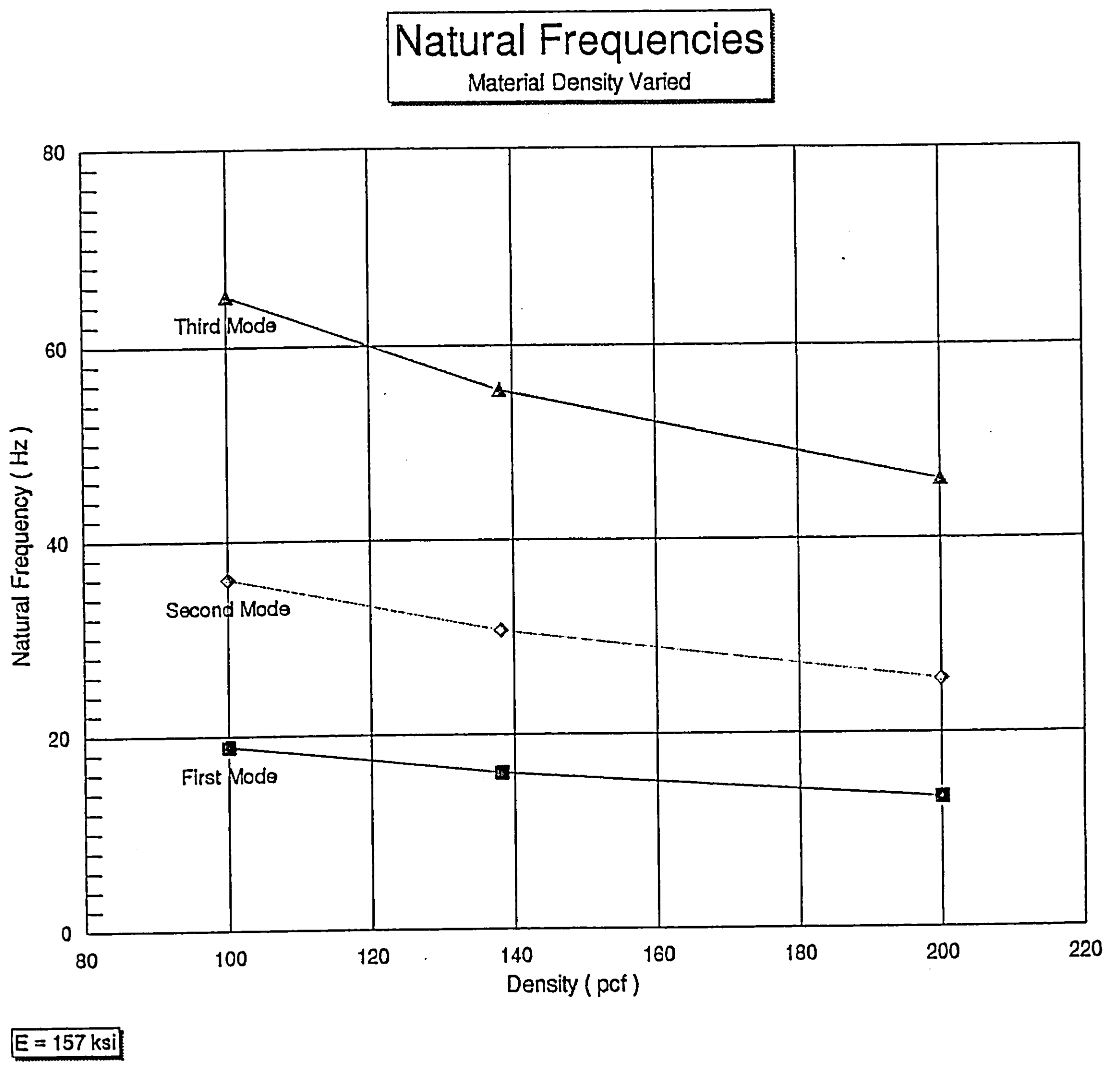
Figure g29

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

Elastic Modulus = 157 ksi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleight Damping Factors



Natural Frequenies (Hz)				
Mode	100	138.2	200	LAB
1	18.8	16.0	13.3	18.0
2	36.0	30.6	25.5	22.0
3	65.1	55.4	46.1	30.0
4	77.5	65.9	54.8	
5	80.9	68.8	57.2	
6	83.5	71.0	59.0	
7	88.7	75.4	62.7	
8	89.8	76.4	63.5	
9	90.6	77.1	64.1	
10	92.4	78.6	65.3	

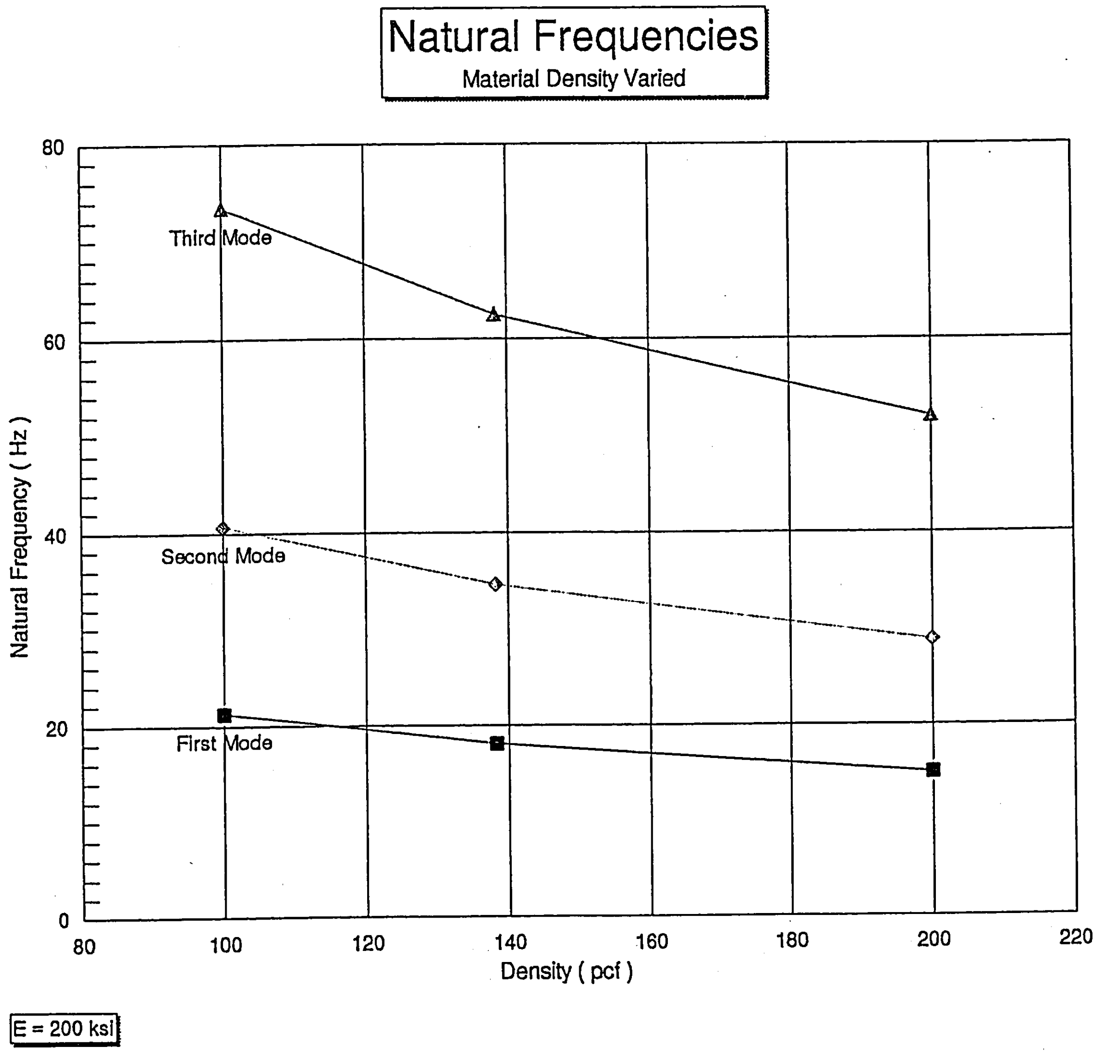
Figure g30

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

Elastic Modulus = 200 ksi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Natural Frequenies (Hz)				
Mode	100	138.2	200	LAB
1	21.3	18.1	15.0	18.0
2	40.7	34.6	28.7	24.0
3	73.5	62.5	52.0	30.0
4	87.5	74.4	61.9	
5	91.3	77.7	64.6	
6	94.2	80.1	66.6	
7	100.1	85.1	70.8	
8	101.3	86.2	71.6	
9	102.3	87.0	72.3	
10	104.3	88.7	73.7	

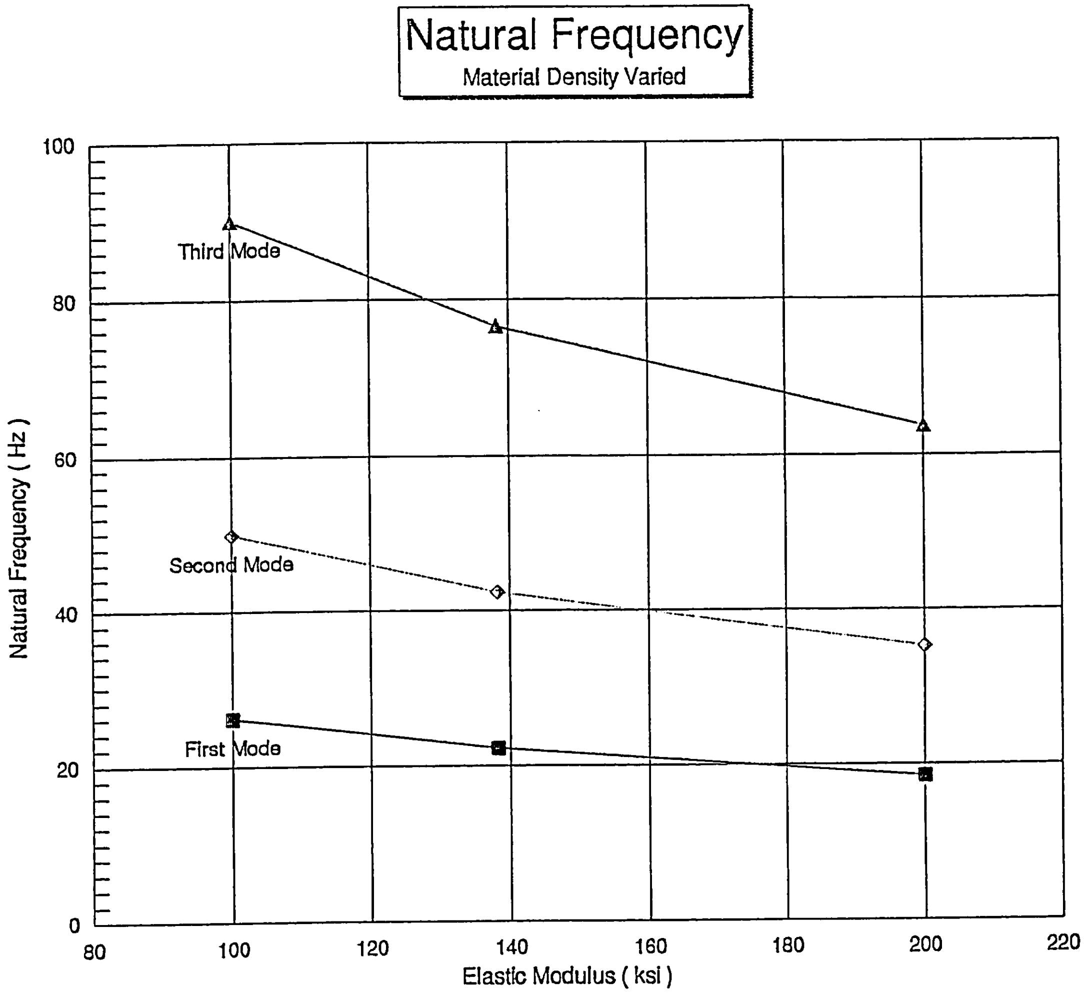
Figure g31

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

Elastic Modulus = 300 ksi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



E = 300 ksi

Natural Frequenies (Hz)				
Mode	100	138.2	200	LAB
1	26.0	22.2	18.4	18.0
2	49.8	42.4	35.2	24.0
3	90.0	76.6	63.7	30.0
4	107.2	91.1	75.8	
5	111.9	95.2	79.1	
6	115.4	98.1	81.6	
7	122.5	104.2	86.7	
8	124.1	105.6	87.7	
9	125.3	106.6	88.6	
10	127.7	108.7	90.3	

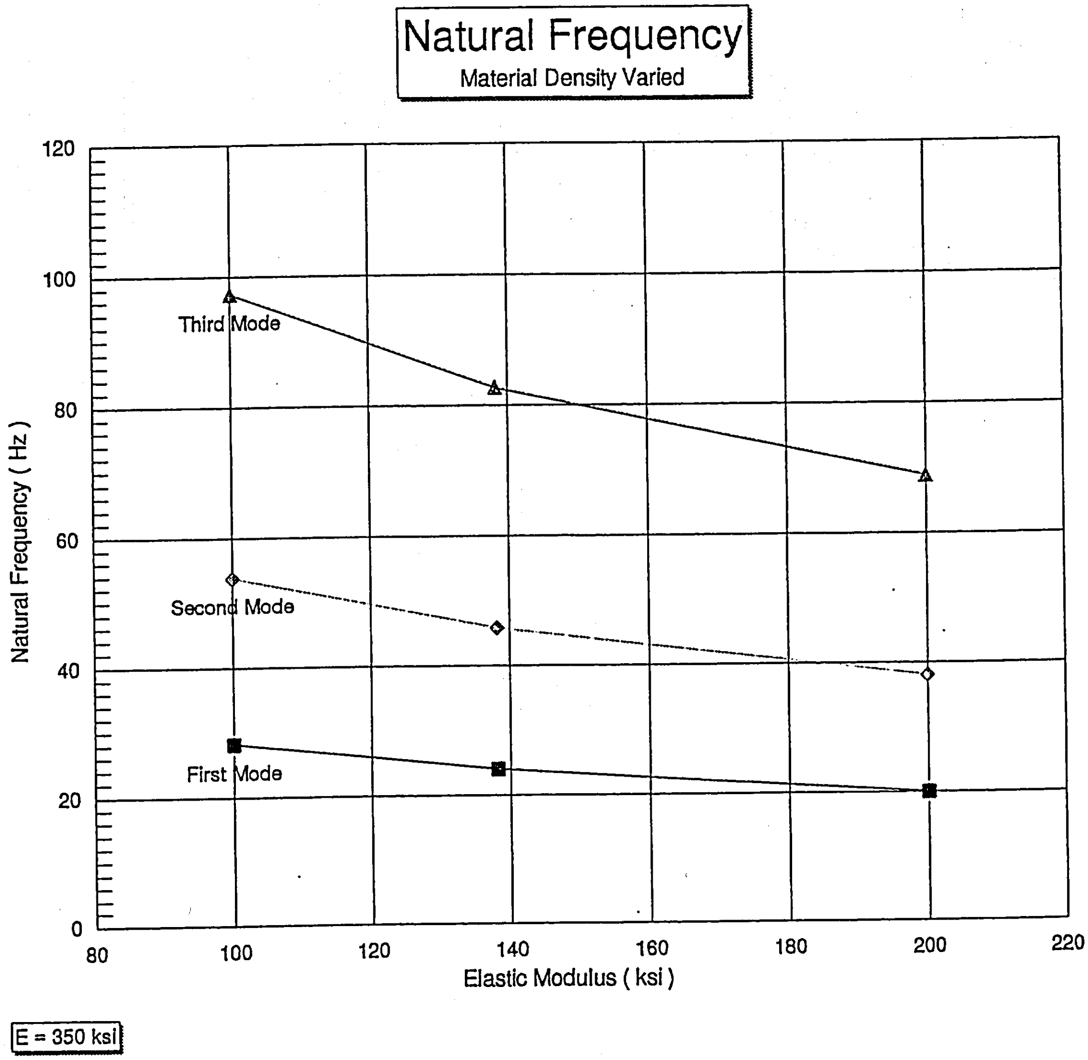
Figure g32

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

Elastic Modulus = 350 ksi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Natural Frequencies (Hz)				
Mode	100	138.2	200	LAB
1	28.1	24.0	19.9	18.0
2	53.8	45.7	38.0	24.0
3	97.2	82.7	68.8	30.0
4	115.7	98.4	81.8	
5	120.8	102.8	85.4	
6	124.6	106.0	88.1	
7	132.4	112.6	93.6	
8	134.0	114.0	94.8	
9	135.3	115.1	95.7	
10	138.0	117.4	97.6	

Figure g33

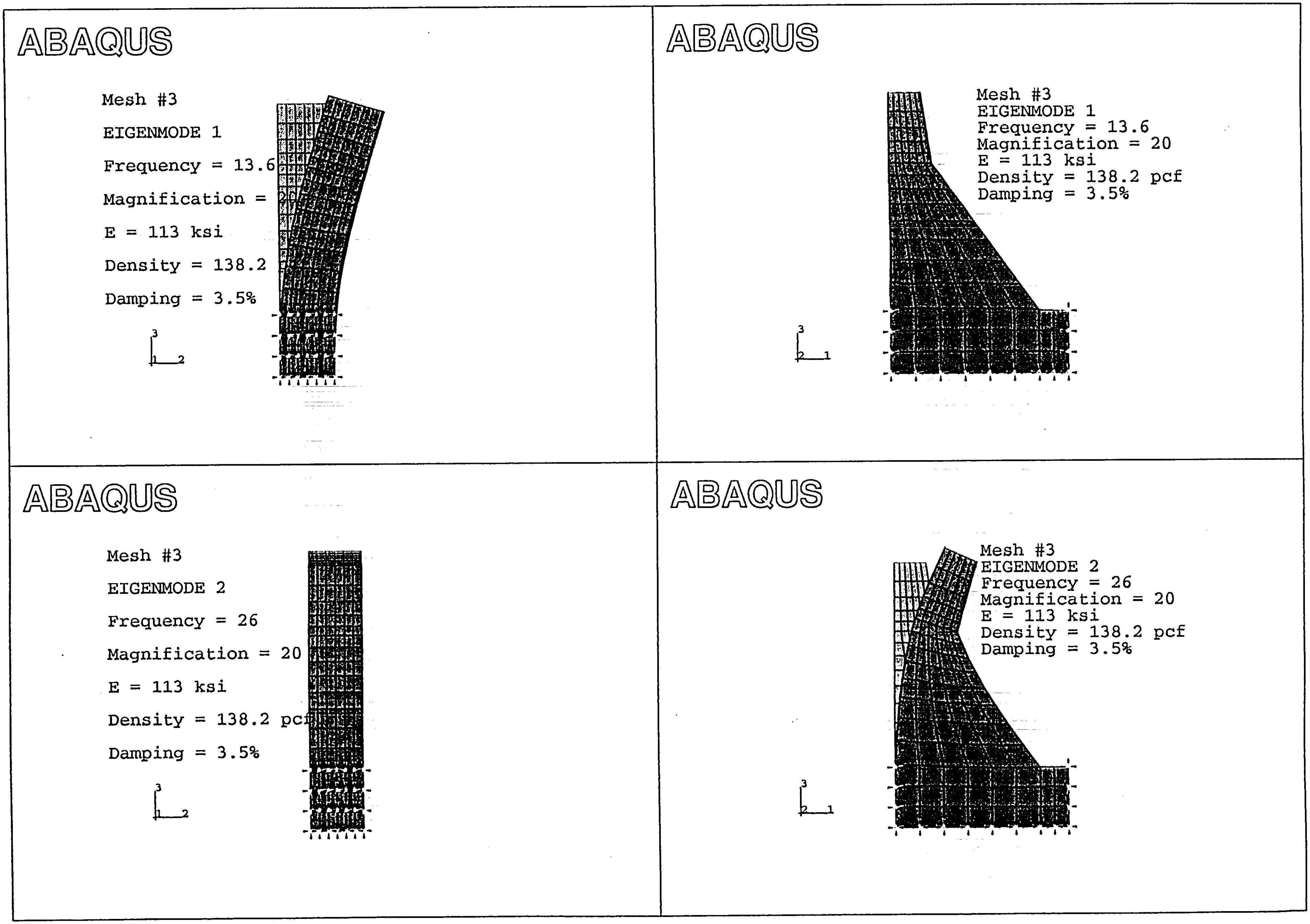

ABAQUS
Mesh #3
EIGENMODE 1
Frequency = 13.6
Magnification =
E = 113 ksi
Density = 138.2
Damping = 3.5%
3
1
2
ABAQUS
Mesh #3
EIGENMODE 1
Frequency = 13.6
Magnification = 20
E = 113 ksi
Density = 138.2 pcf
Damping = 3.5%
3
2
1
ABAQUS
Mesh #3
EIGENMODE 2
Frequency = 26
Magnification = 20
E = 113 ksi
Density = 138.2 pc
Damping = 3.5%
3
1
2
ABAQUS
Mesh #3
EIGENMODE 2
Frequency = 26
Magnification = 20
E = 113 ksi
Density = 138.2 pcf
Damping = 3.5%
3
2
1

Figure g34

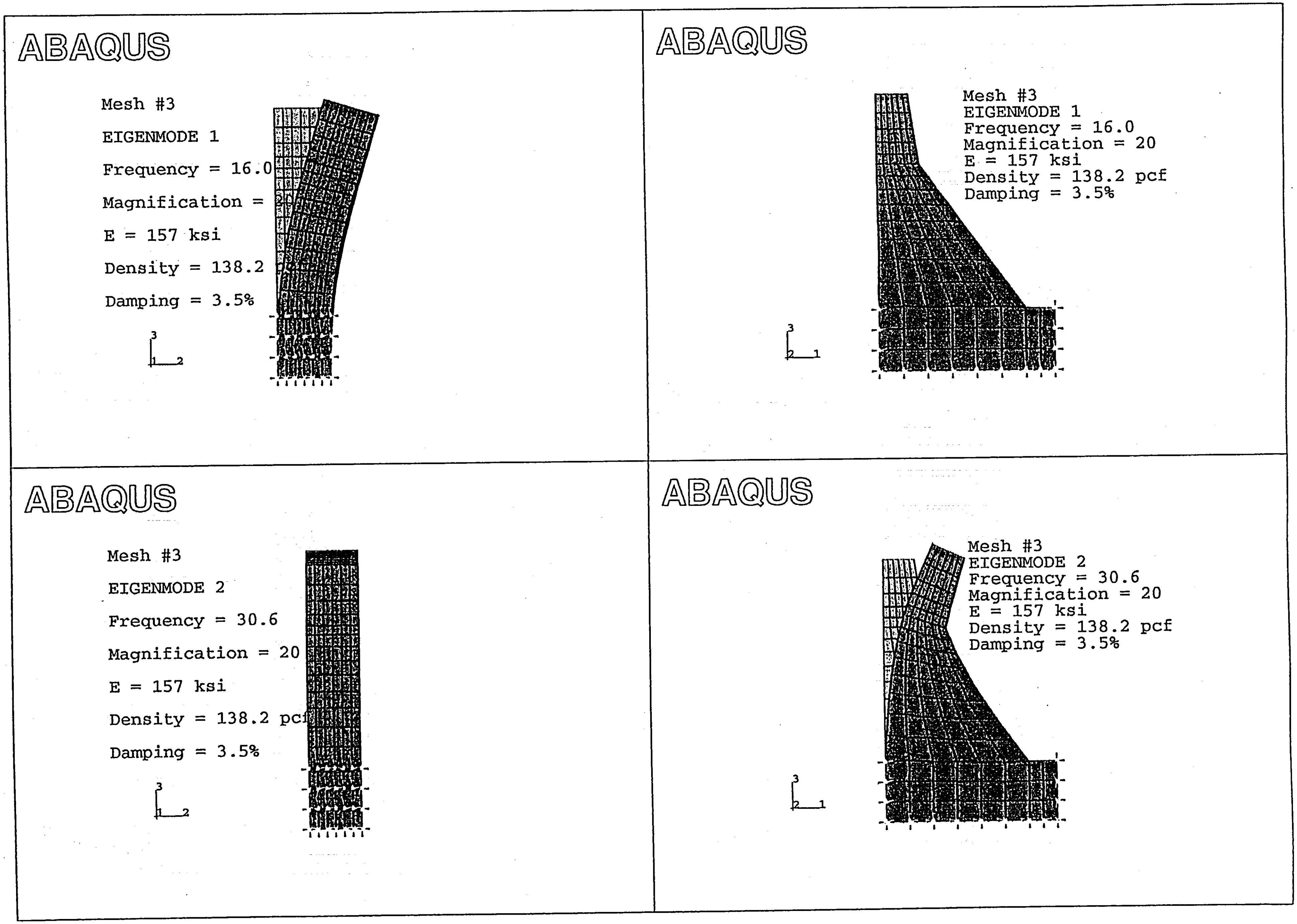

ABAQUS
Mesh #3
EIGENMODE 1
Frequency = 16.0
Magnification = 20
E = 157 ksi
Density = 138.2 pcf
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 1
Frequency = 16.0
Magnification = 20
E = 157 ksi
Density = 138.2 pcf
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 2
Frequency = 30.6
Magnification = 20
E = 157 ksi
Density = 138.2 pcf
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 2
Frequency = 30.6
Magnification = 20
E = 157 ksi
Density = 138.2 pcf
Damping = 3.5%

Figure 935

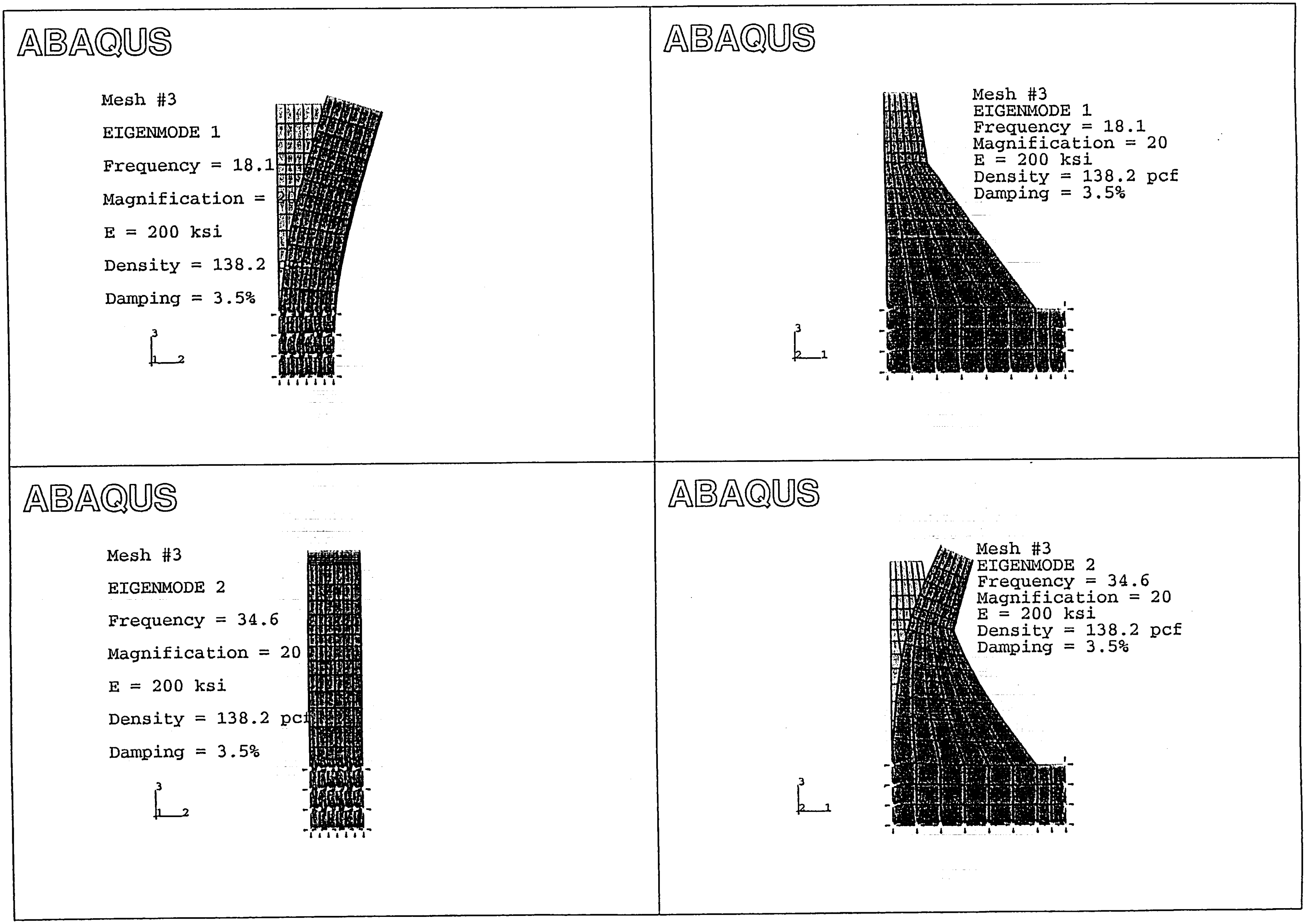

ABAQUS
Mesh #3
EIGENMODE 1
Frequency = 18.1
Magnification =
E = 200 ksi
Density = 138.2
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 1
Frequency = 18.1
Magnification = 20
E = 200 ksi
Density = 138.2 pcf
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 2
Frequency = 34.6
Magnification = 20
E = 200 ksi
Density = 138.2 pcf
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 2
Frequency = 34.6
Magnification = 20
E = 200 ksi
Density = 138.2 pcf
Damping = 3.5%

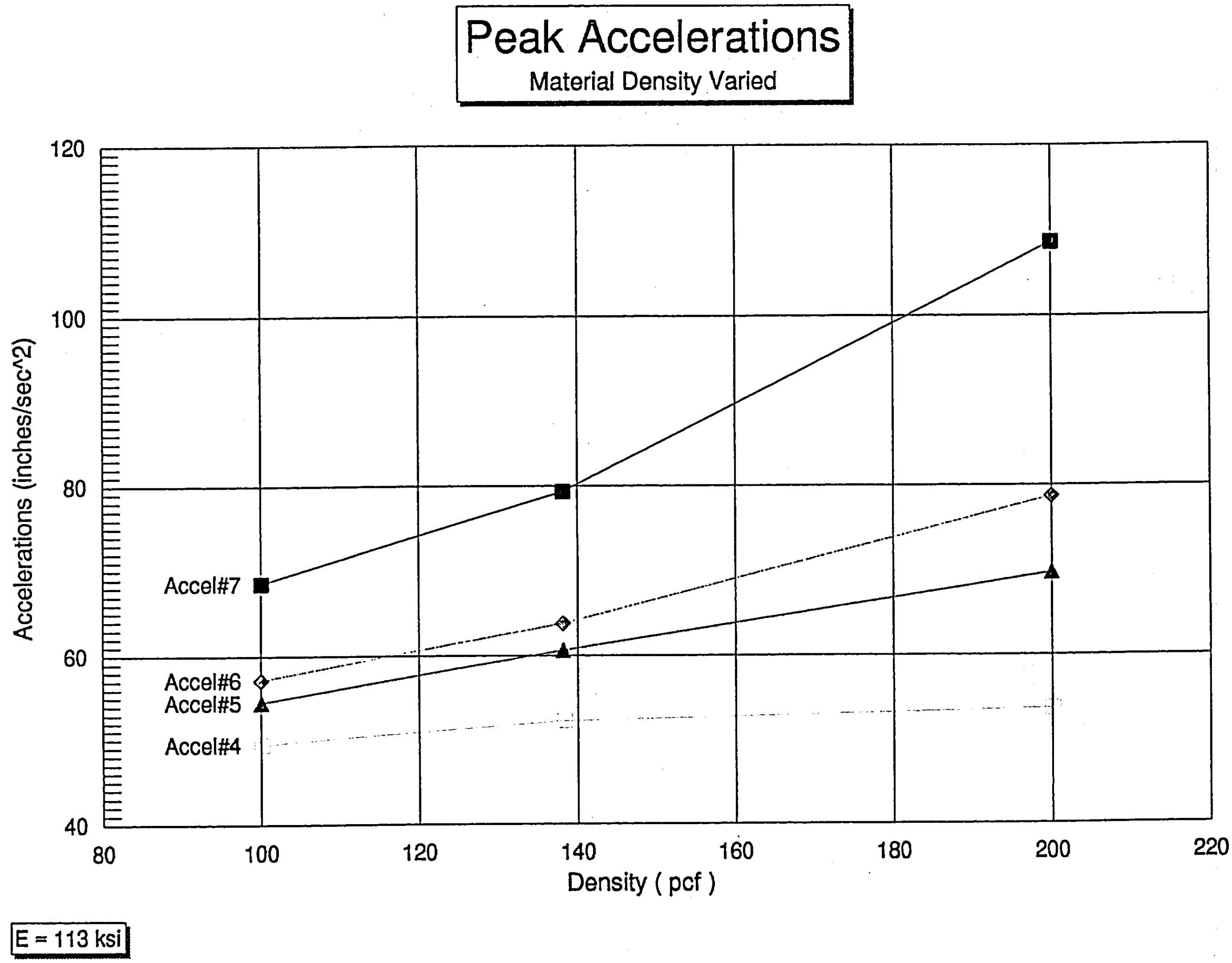
Figure 936

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 113,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)				
	100	138.2	200	**LAB**
Accel#7	68.51	79.31	108.60	53.26
Accel#6	57.18	63.80	78.68	51.72
Accel#5	54.49	60.60	69.67	49.26
Accel#4	49.40	52.28	53.65	47.72

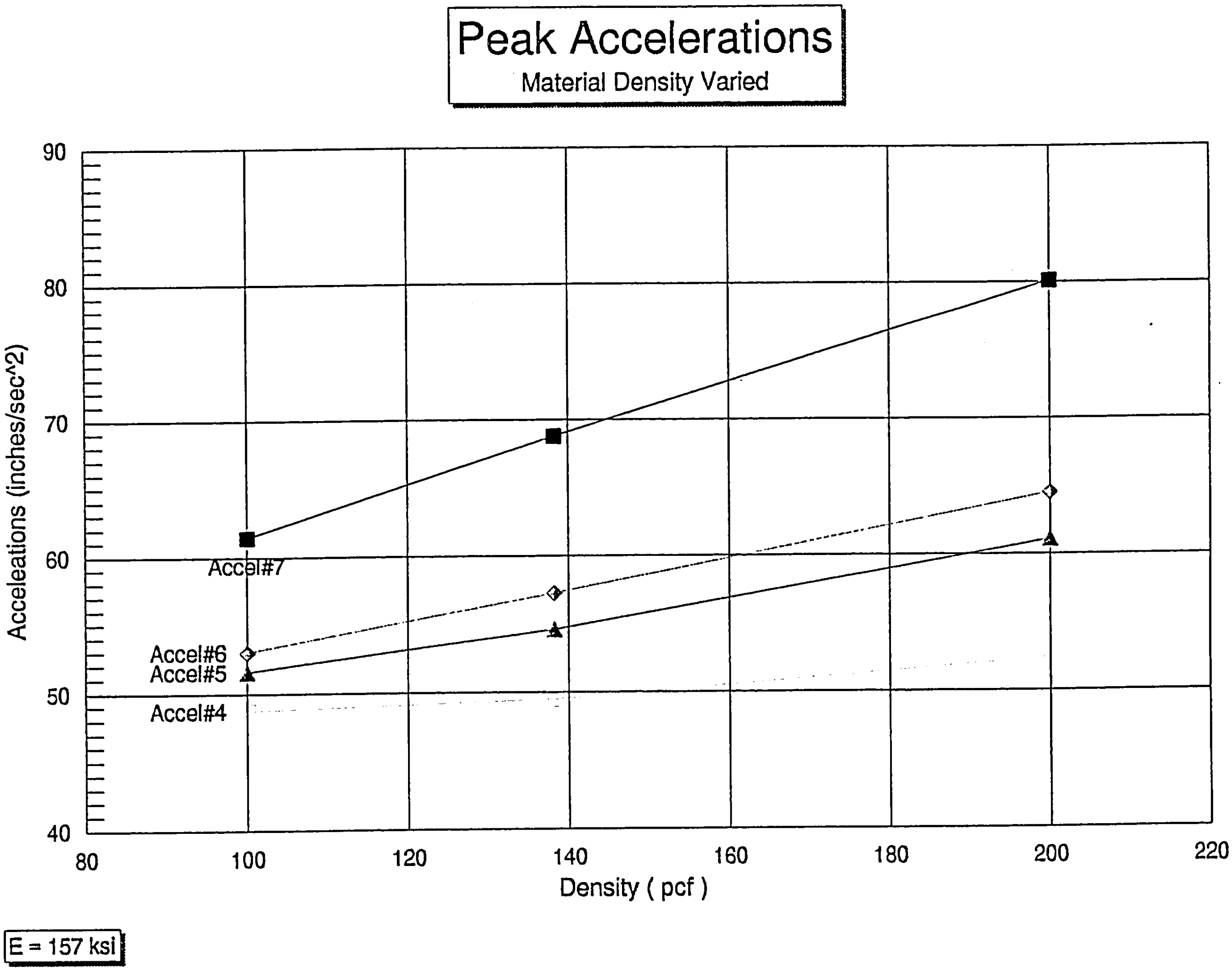
Figure g37

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 157,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

	100	138.2	200	LAB
Accel#7	61.39	68.75	80.10	53.26
Accel#6	52.99	57.19	64.49	51.72
Accel#5	51.54	54.54	61.04	49.26
Accel#4	48.70	49.47	52.36	47.72

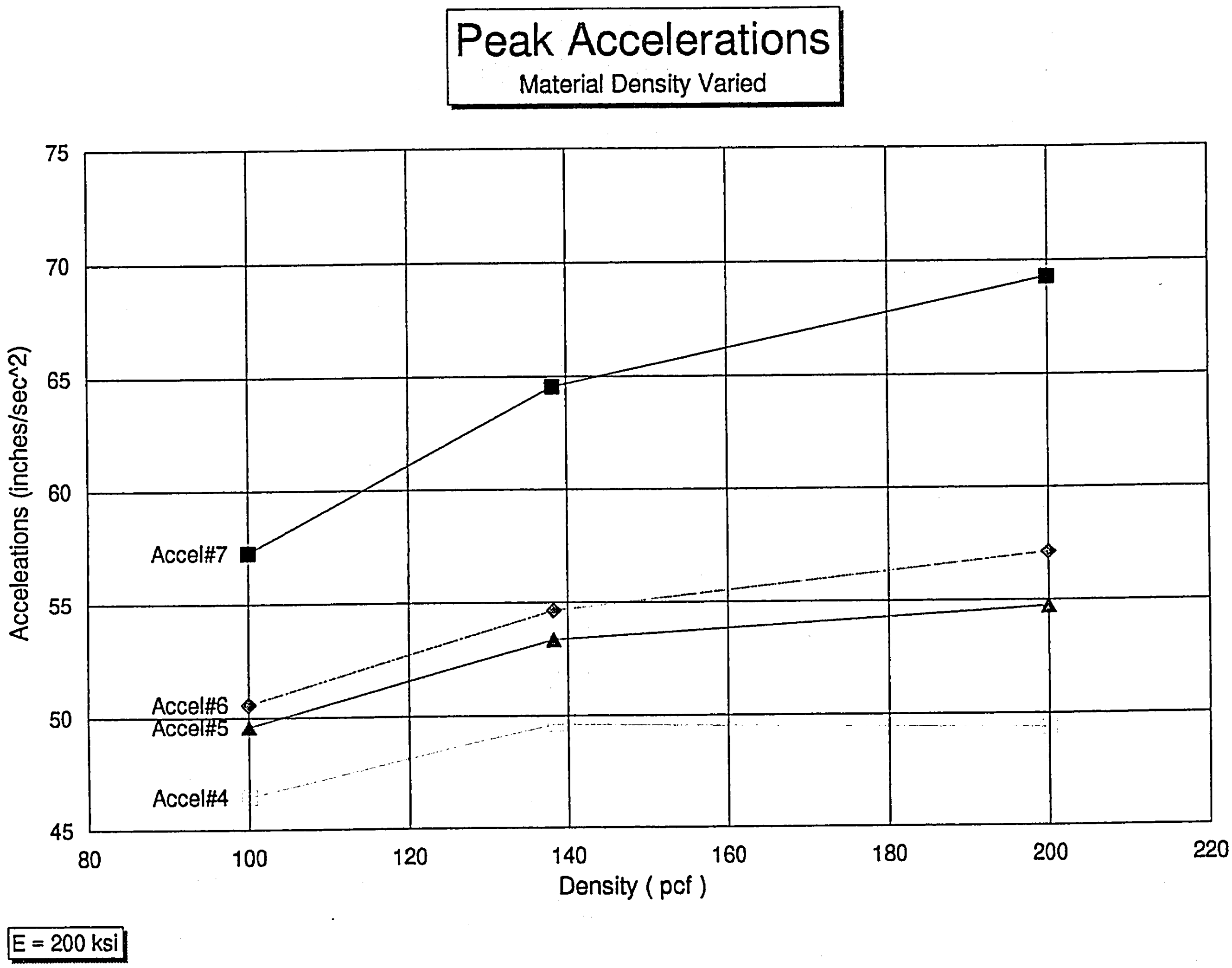
Figure g38

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 200,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)				
	100	138.2	200	LAB
Accel#7	57.25	64.53	69.27	53.26
Accel#6	50.56	54.64	57.12	51.72
Accel#5	49.57	53.34	54.73	49.26
Accel#4	46.42	49.60	49.36	47.72

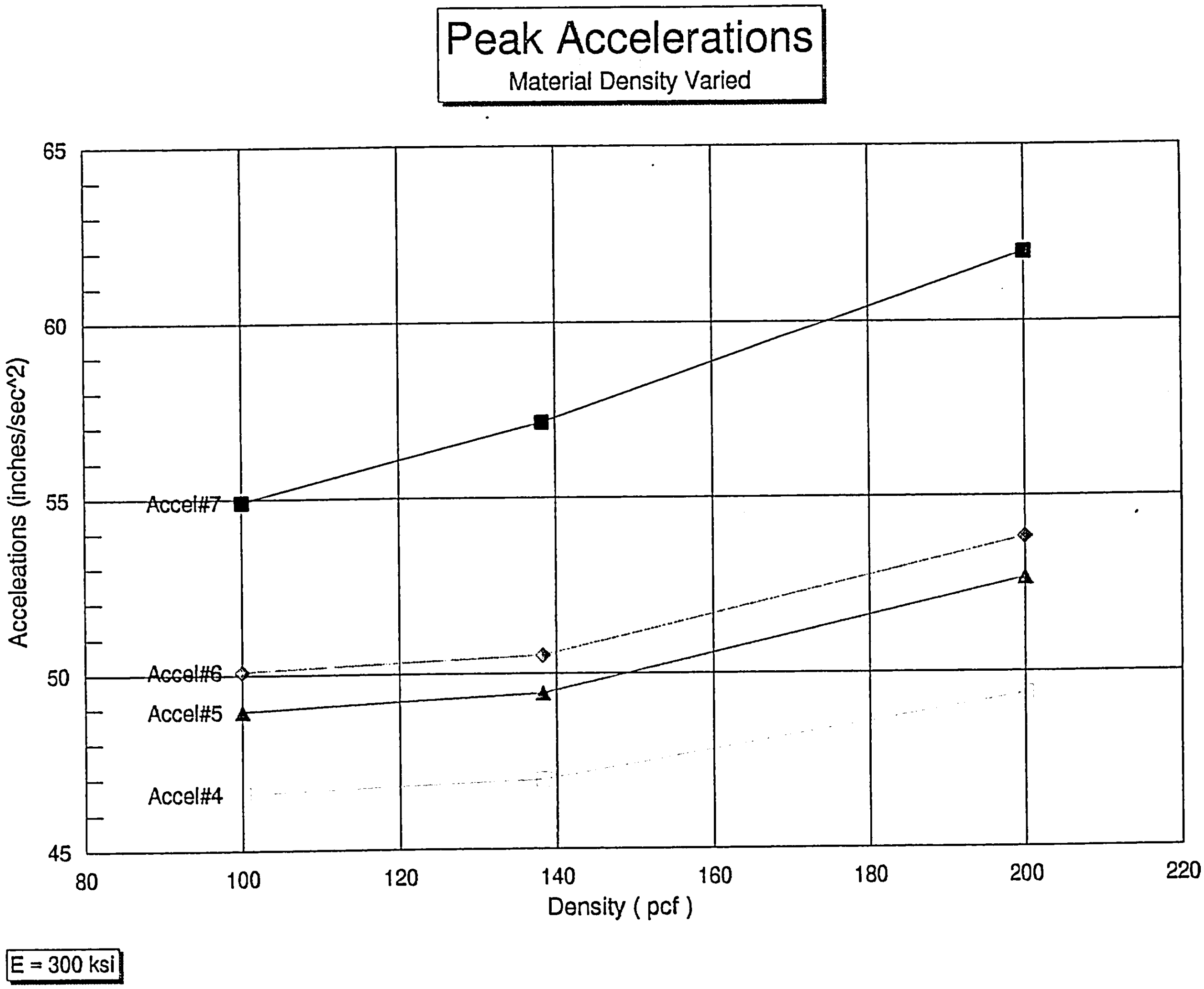
Figure g39

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 300,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)				
	100	138.2	200	LAB
Accel#7	54.90	57.14	61.96	53.26
Accel#6	50.07	50.50	53.82	51.72
Accel#5	48.93	49.42	52.65	49.26
Accel#4	46.59	46.97	49.36	47.72

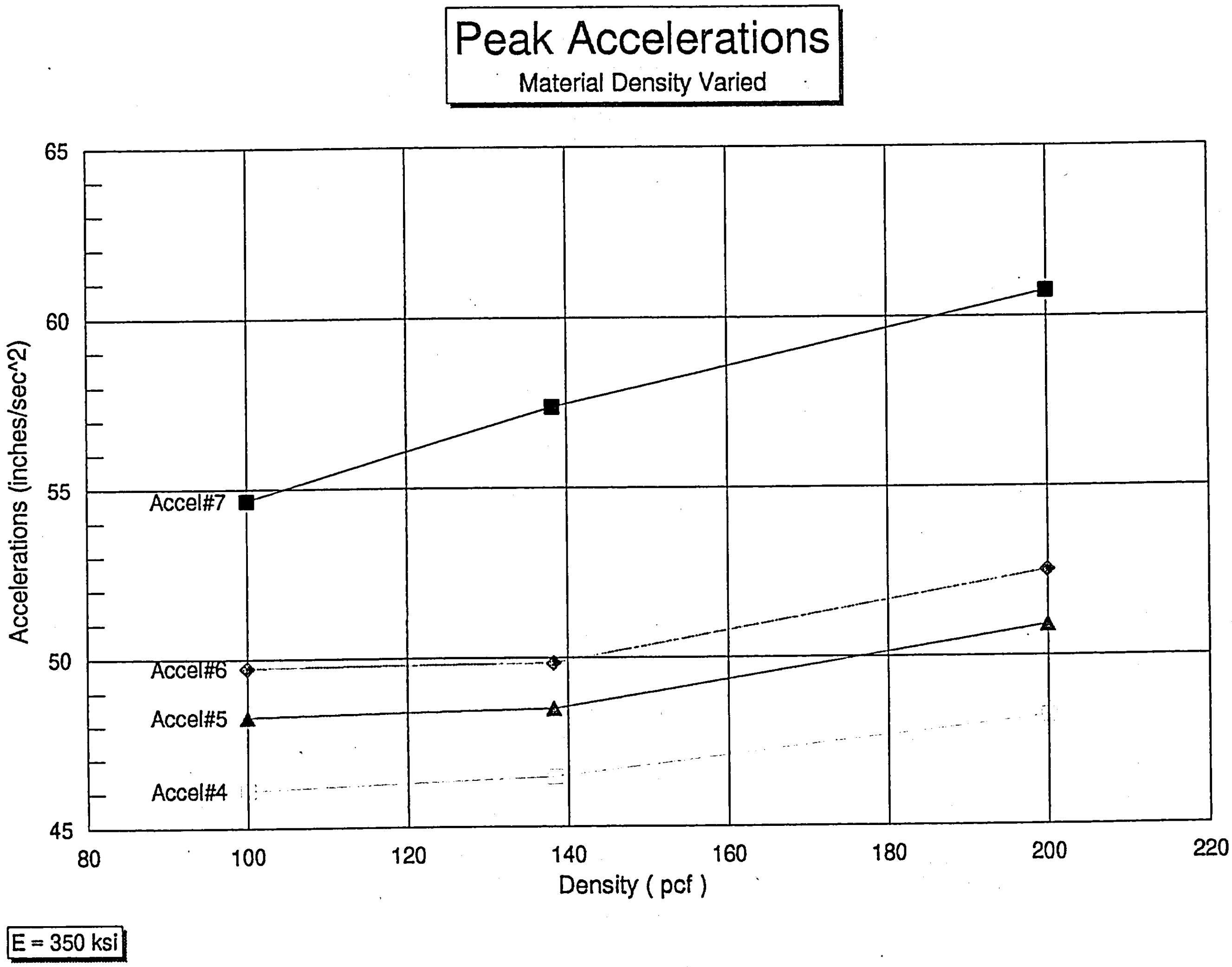
Figure g40

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 350,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)				
	100	138.2	200	LAB
Accel#7	54.66	57.39	60.74	53.26
Accel#6	49.73	49.85	52.52	51.72
Accel#5	48.29	48.51	50.91	49.26
Accel#4	46.09	46.47	48.24	47.72

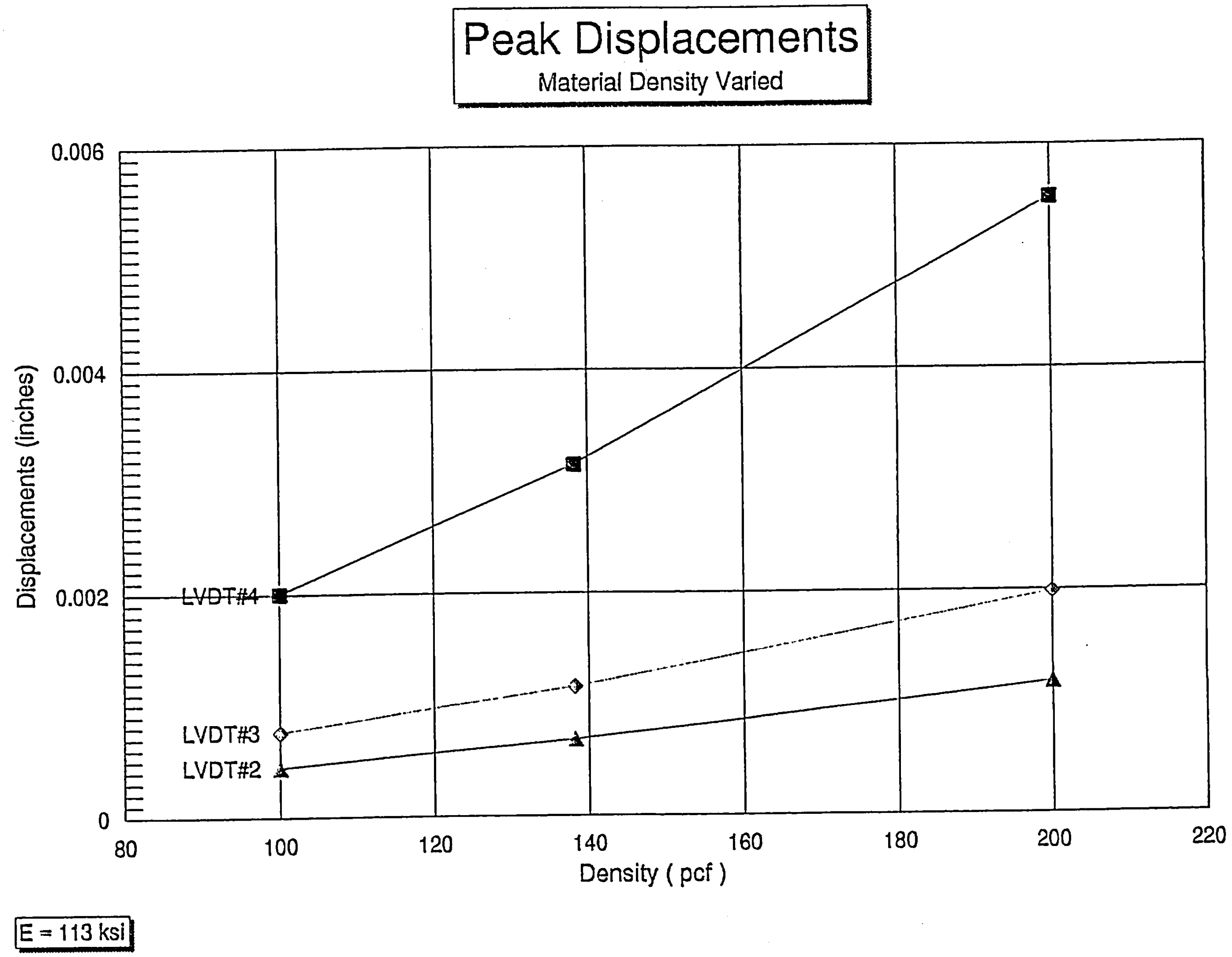
Figure g41

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 113,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (inches)				
	100	138.2	200	LAB
LVDT#4	2.0E-03	3.1E-03	5.5E-03	7.2E-04
LVDT#3	7.6E-04	1.2E-03	2.0E-03	3.1E-04
LVDT#2	4.5E-04	6.9E-04	1.2E-03	2.1E-04

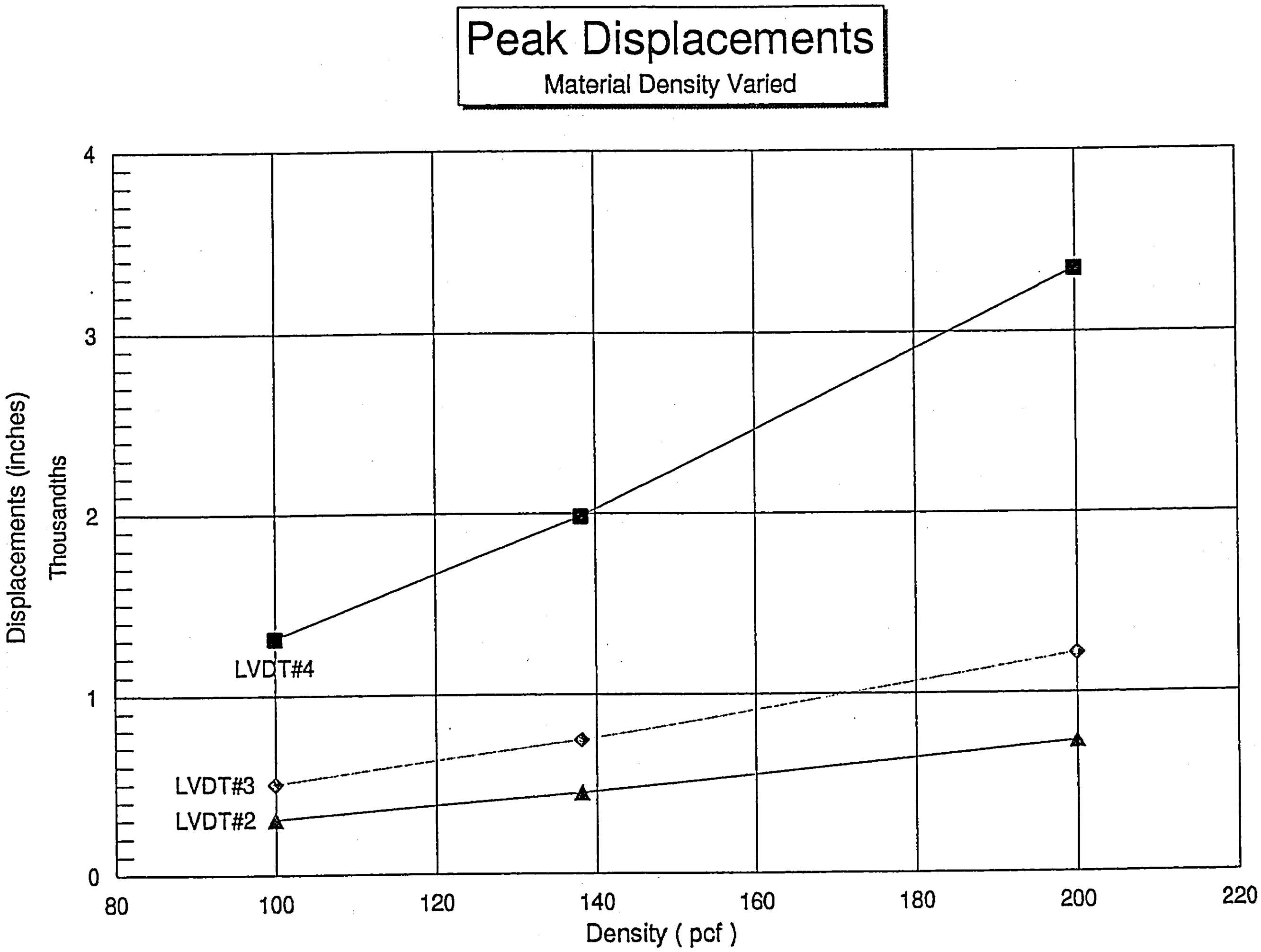
Figure g42

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 157,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



E = 157 ksi

Peak Displacements (inches)

	100	138.2	200	LAB
LVDT#4	1.3E-03	2.0E-03	3.3E-03	7.2E-04
LVDT#3	5.0E-04	7.4E-04	1.2E-03	3.1E-04
LVDT#2	3.0E-04	4.4E-04	7.2E-04	2.1E-04

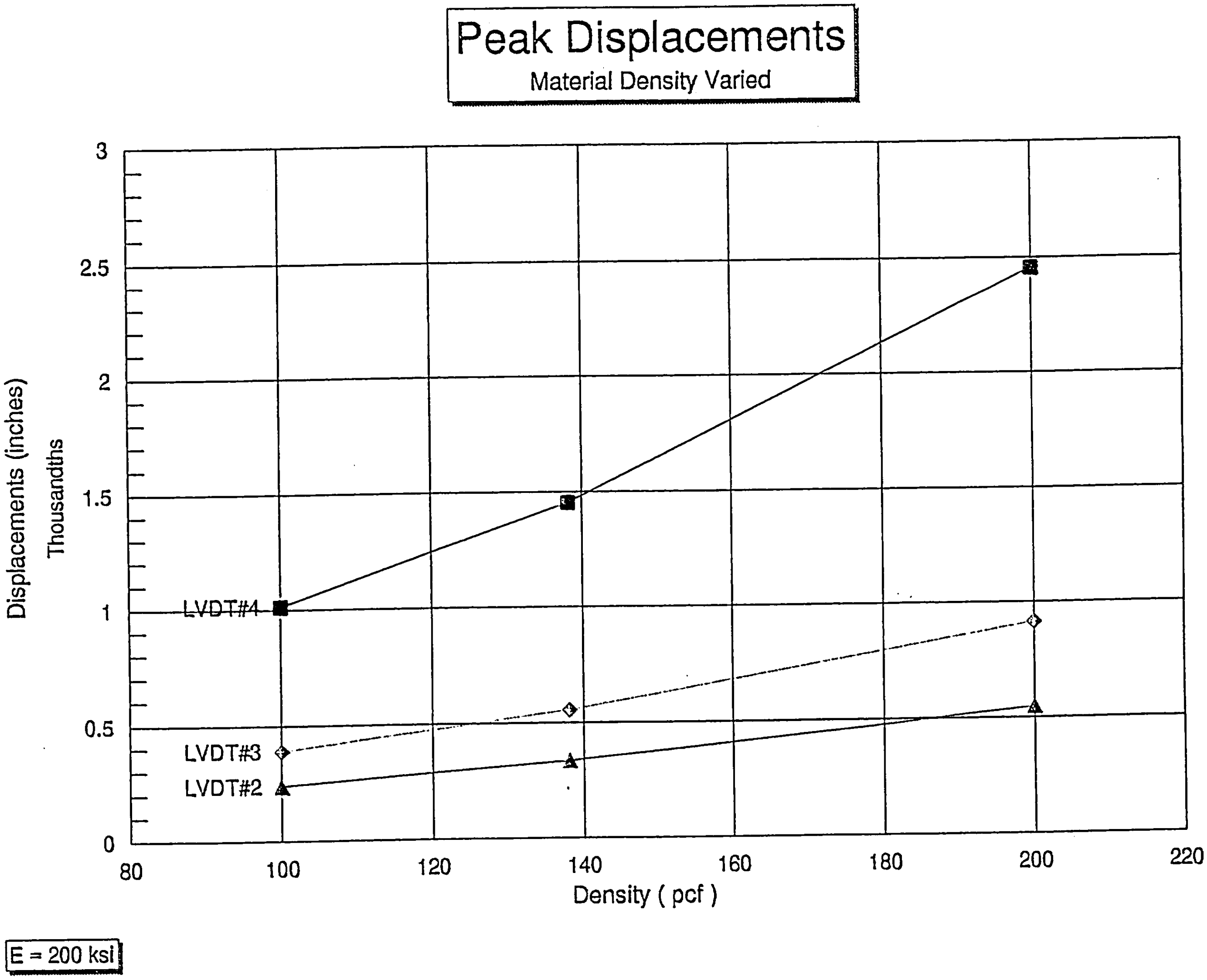
Figure g43

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 200,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (inches)				
	100	138.2	200	LAB
LVDT#4	1.0E-03	1.5E-03	2.5E-03	7.2E-04
LVDT#3	3.9E-04	5.5E-04	9.1E-04	3.1E-04
LVDT#2	2.4E-04	3.3E-04	5.5E-04	2.1E-04

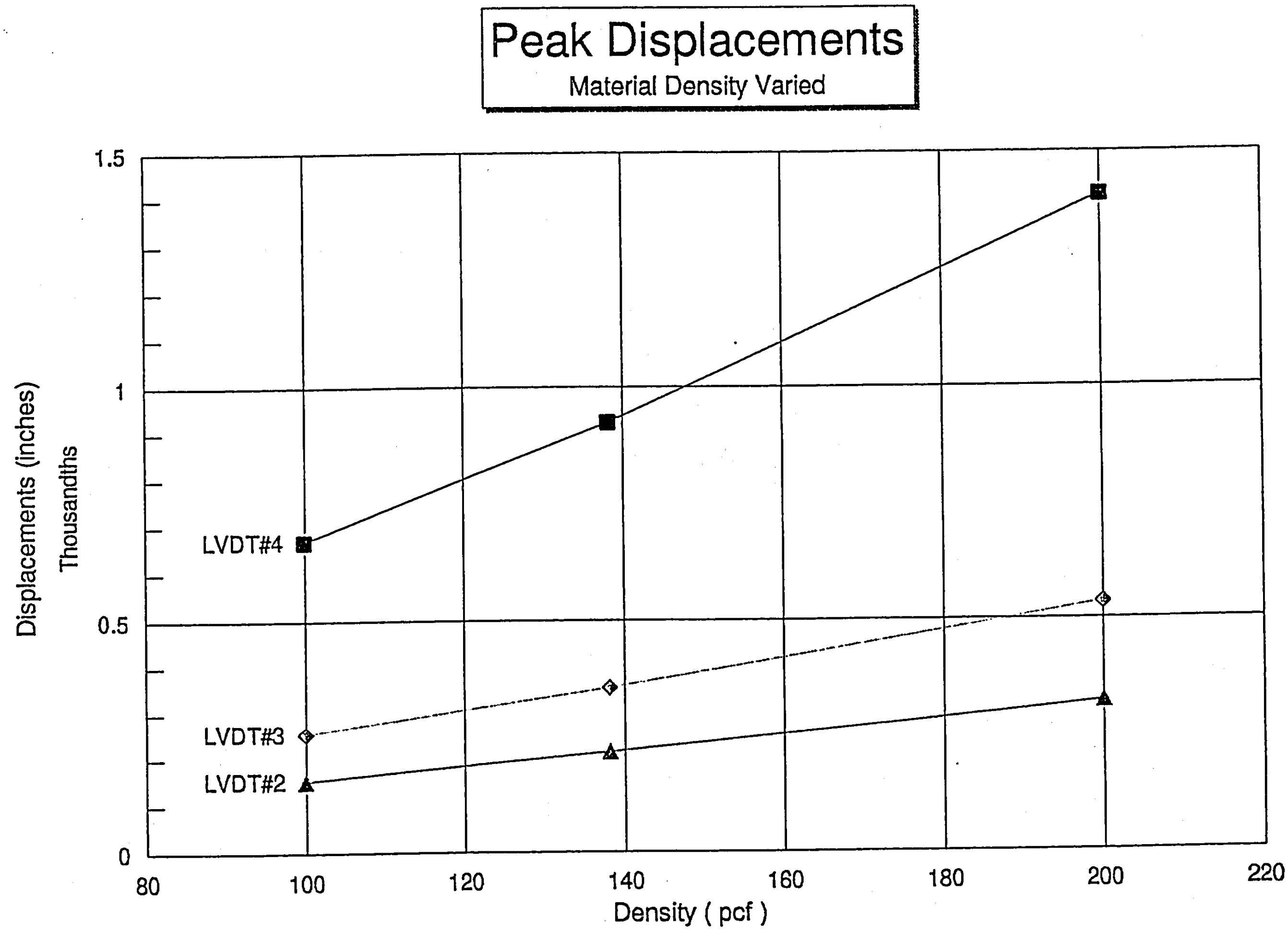
Figure g44

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 300,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



E = 300 ksi

Peak Displacements (inches)				
	100	138.2	200	LAB
LVDT#4	6.7E-04	9.2E-04	1.4E-03	7.2E-04
LVDT#3	2.6E-04	3.6E-04	5.3E-04	3.1E-04
LVDT#2	1.5E-04	2.2E-04	3.2E-04	2.1E-04

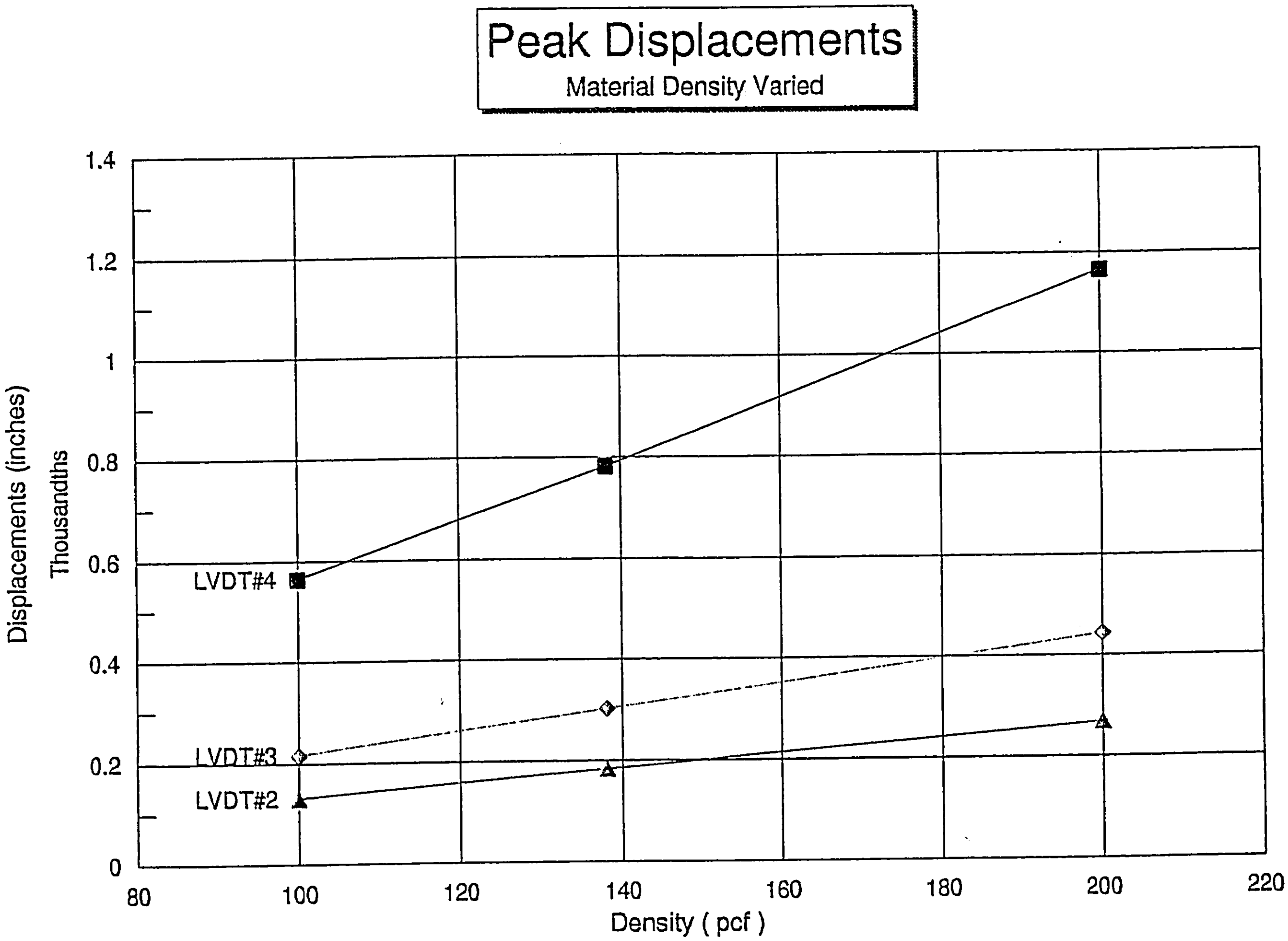
Figure g45

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 350,000 psi
Material Density = (100, 138, 200 pcf)

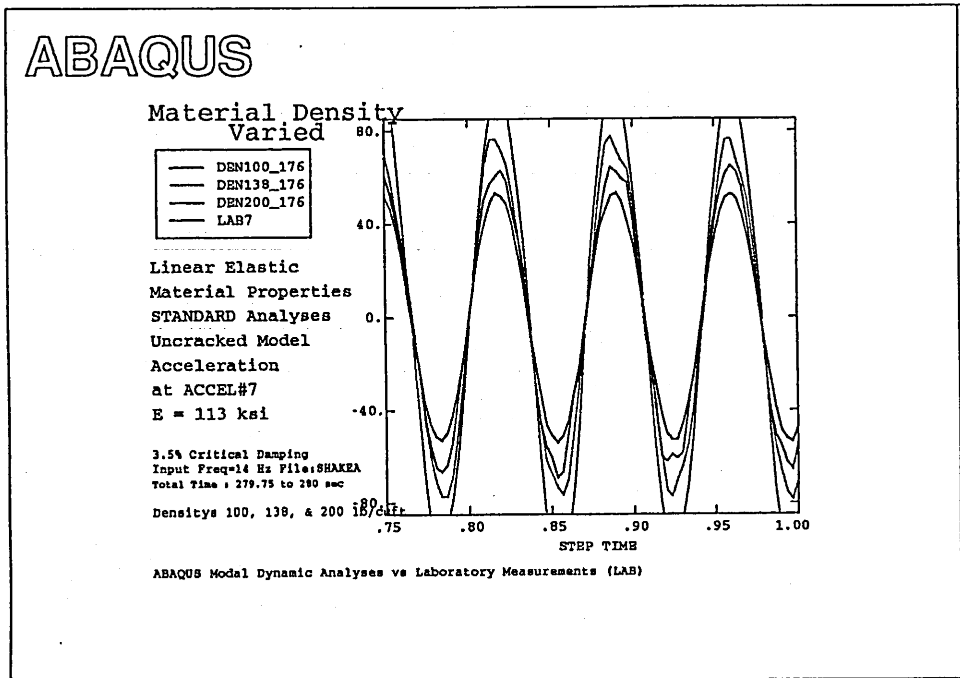
Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248

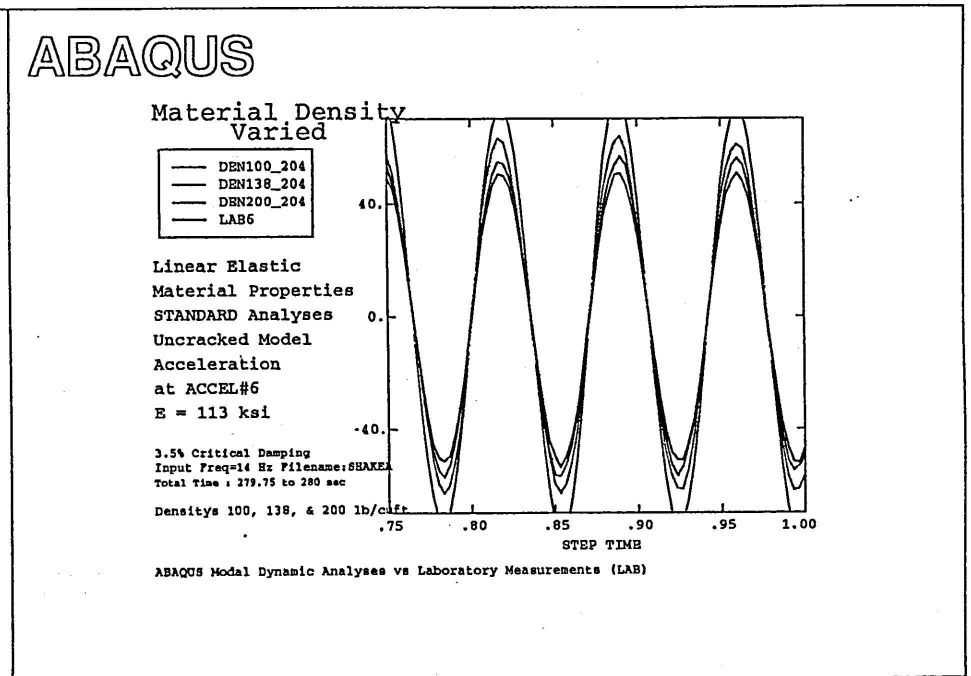


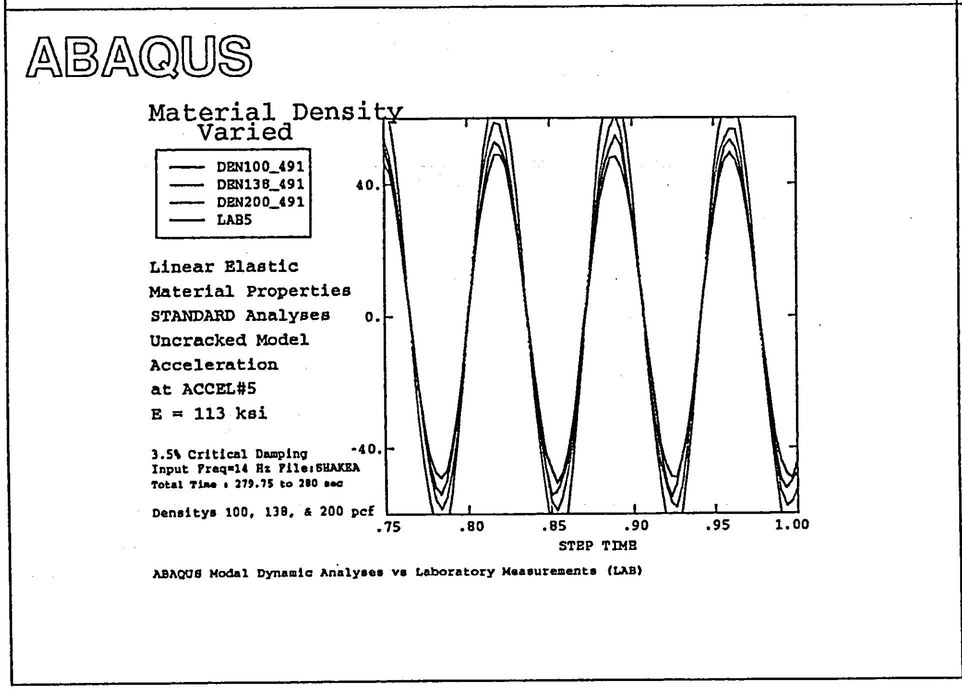
E = 350 ksi

Peak Displacements (inches)				
	100	138.2	200	LAB
LVDT#4	5.6E-04	7.8E-04	1.2E-03	7.2E-04
LVDT#3	2.2E-04	3.0E-04	4.4E-04	3.1E-04
LVDT#2	1.3E-04	1.8E-04	2.7E-04	2.1E-04

Figure g46


ABAQUS
Material Density Varied
DEN100_176
DEN138_176
DEN200_176
LAB7
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
E = 113 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
80.
40.
0.
-40.
-80.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)


ABAQUS
Material Density Varied
DEN100_204
DEN138_204
DEN200_204
LAB6
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
E = 113 ksi
3.5% Critical Damping
Input Freq=14 Hz Filename:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)


ABAQUS
Material Density Varied
DEN100_491
DEN138_491
DEN200_491
LAB5
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
E = 113 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 pcf
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

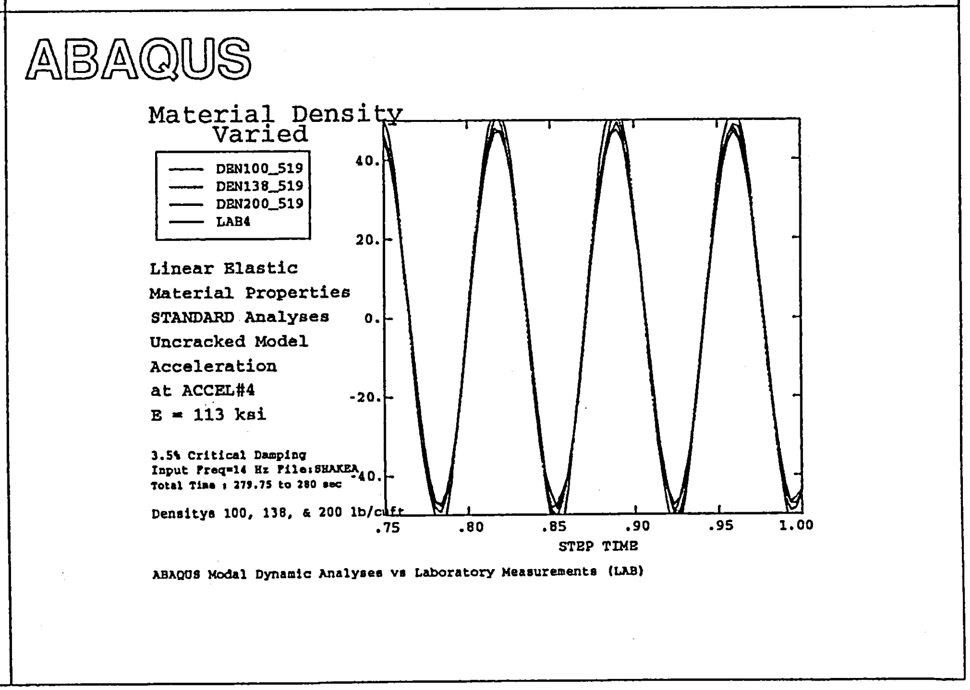
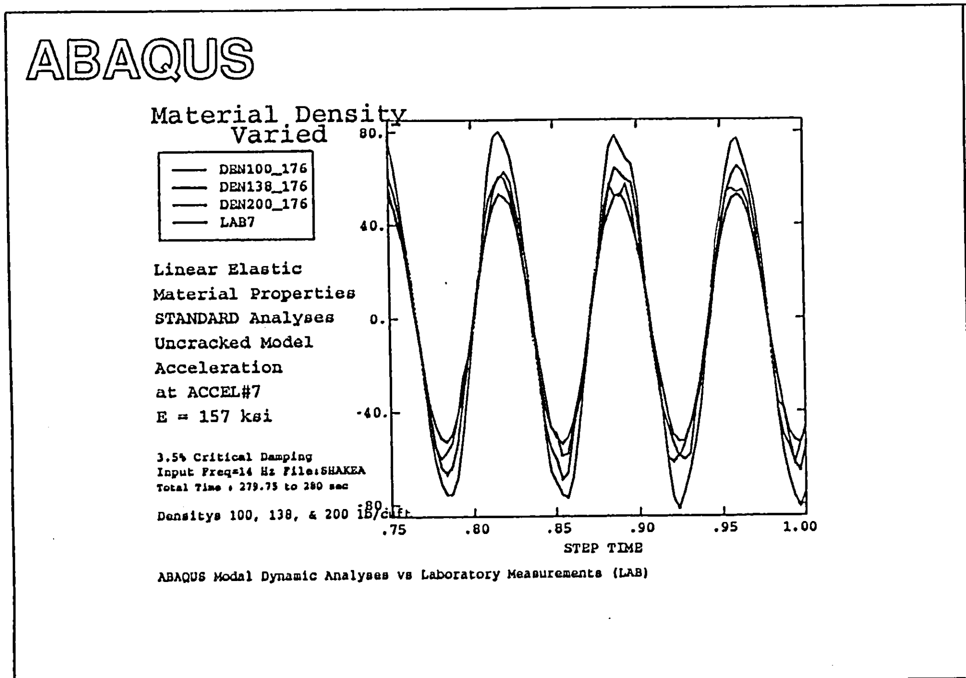
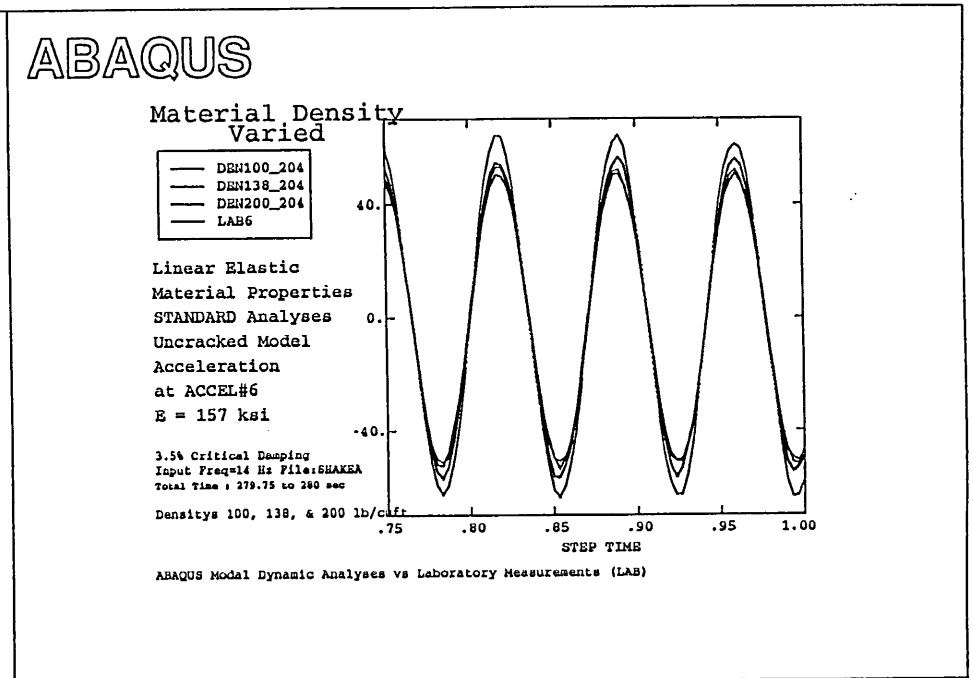
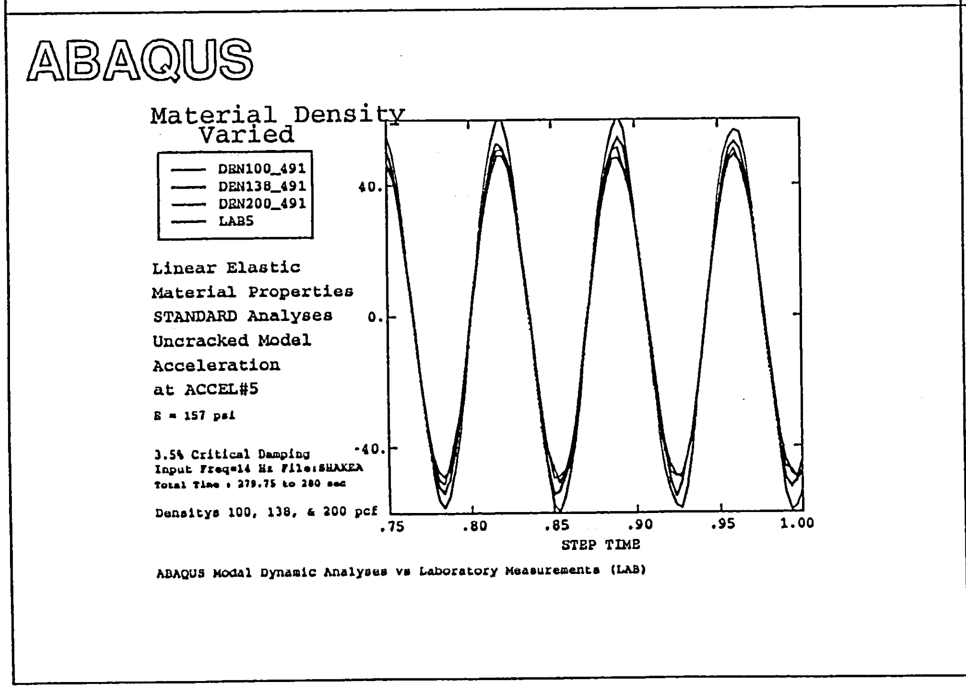

ABAQUS
Material Density Varied
DEN100_519
DEN138_519
DEN200_519
LAB4
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
E = 113 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
20.
0.
-20.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

Figure 947


ABAQUS
Material Density Varied
DEN100_176
DEN138_176
DEN200_176
LAB7
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
E = 157 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
80.
40.
0.
-40.
-80.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)


ABAQUS
Material Density Varied
DEN100_204
DEN138_204
DEN200_204
LAB6
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
E = 157 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)


ABAQUS
Material Density Varied
DEN100_491
DEN138_491
DEN200_491
LAB5
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
E = 157 psi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 pcf
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

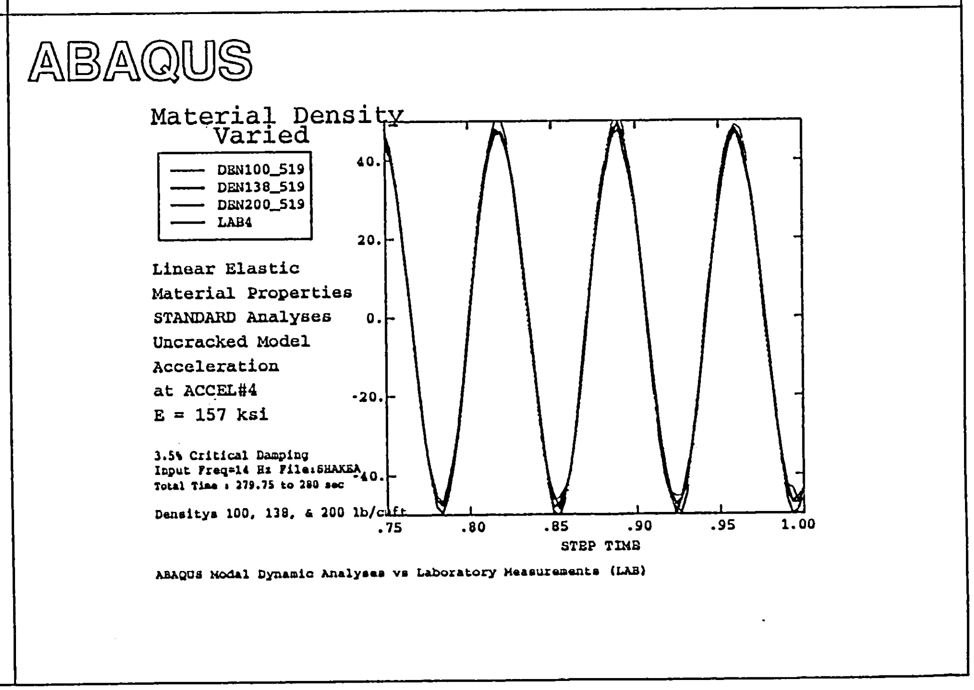

ABAQUS
Material Density Varied
DEN100_519
DEN138_519
DEN200_519
LAB4
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
E = 157 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
20.
0.
-20.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

Figure g48

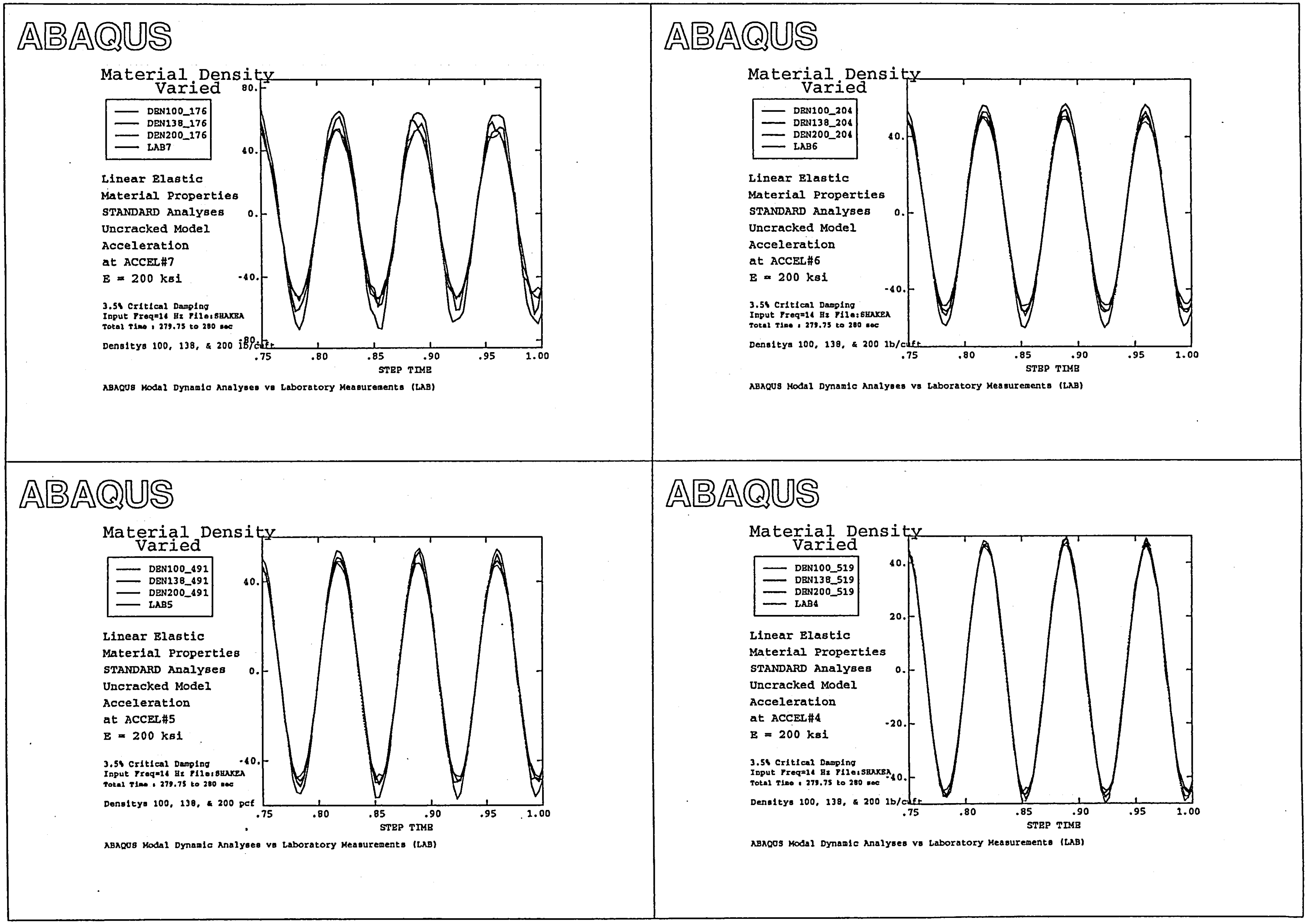
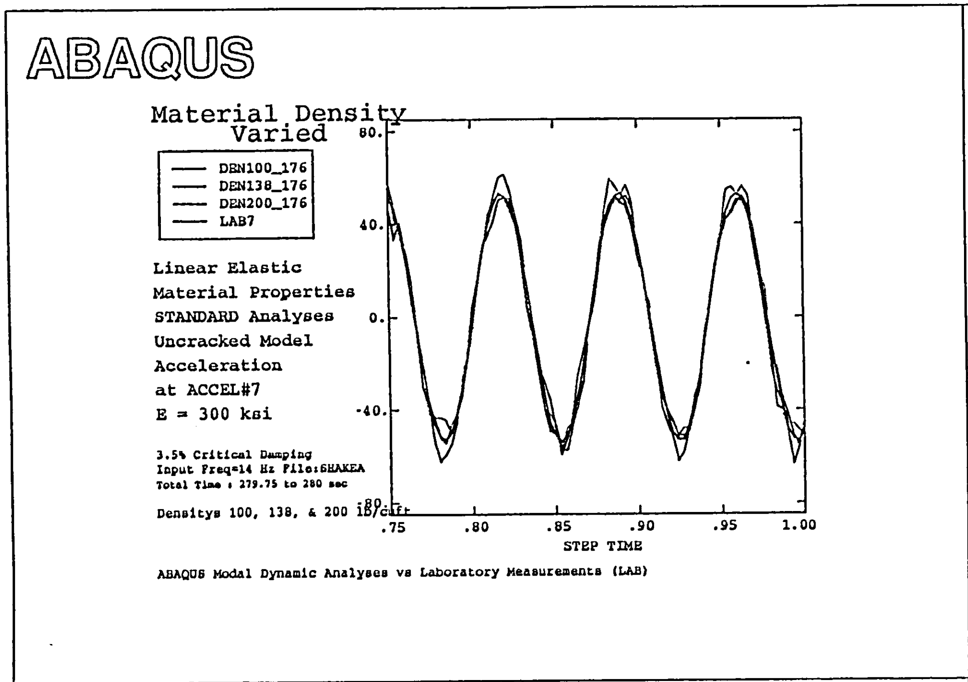
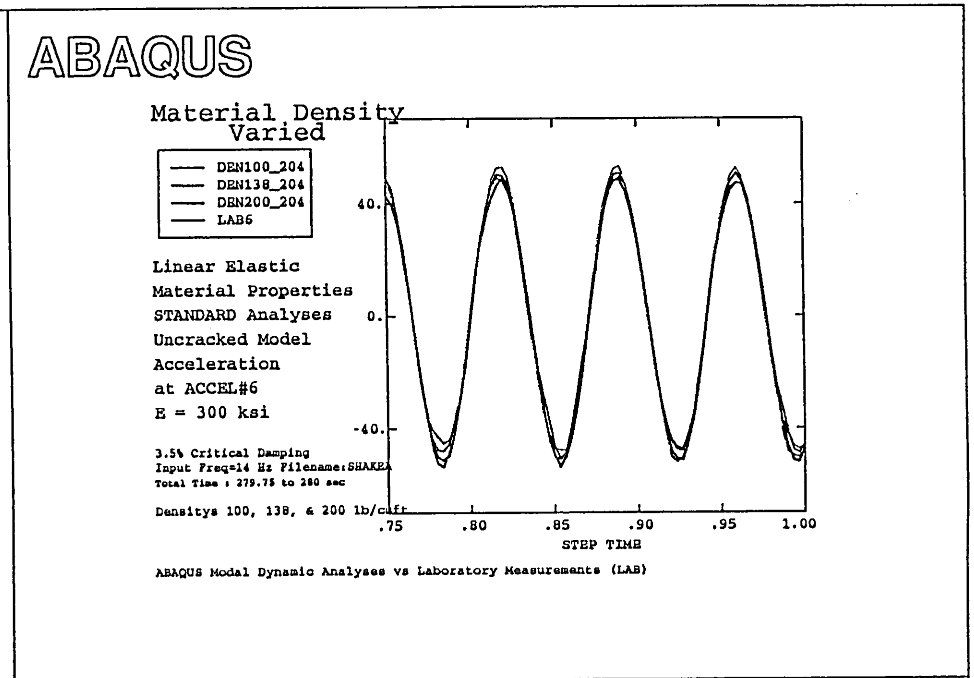

ABAQUS
Material Density Varied
DEN100_176
DEN138_176
DEN200_176
LAB7
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
E = 200 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)
ABAQUS
Material Density Varied
DEN100_204
DEN138_204
DEN200_204
LAB6
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
E = 200 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)
ABAQUS
Material Density Varied
DEN100_491
DEN138_491
DEN200_491
LAB5
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
E = 200 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 pcf
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)
ABAQUS
Material Density Varied
DEN100_519
DEN138_519
DEN200_519
LAB4
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
E = 200 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

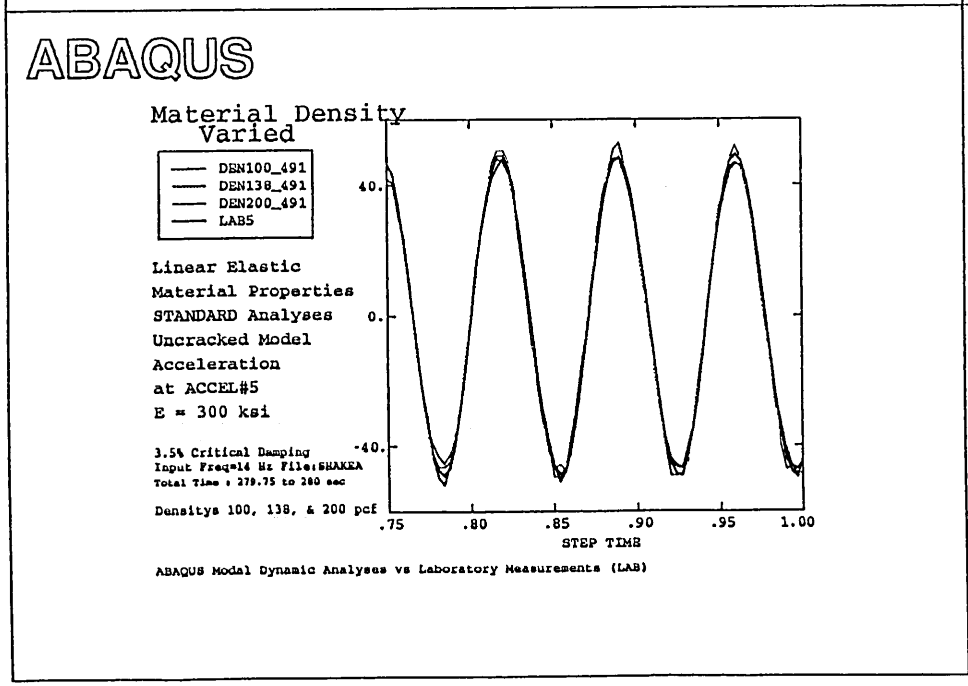
Figure 949



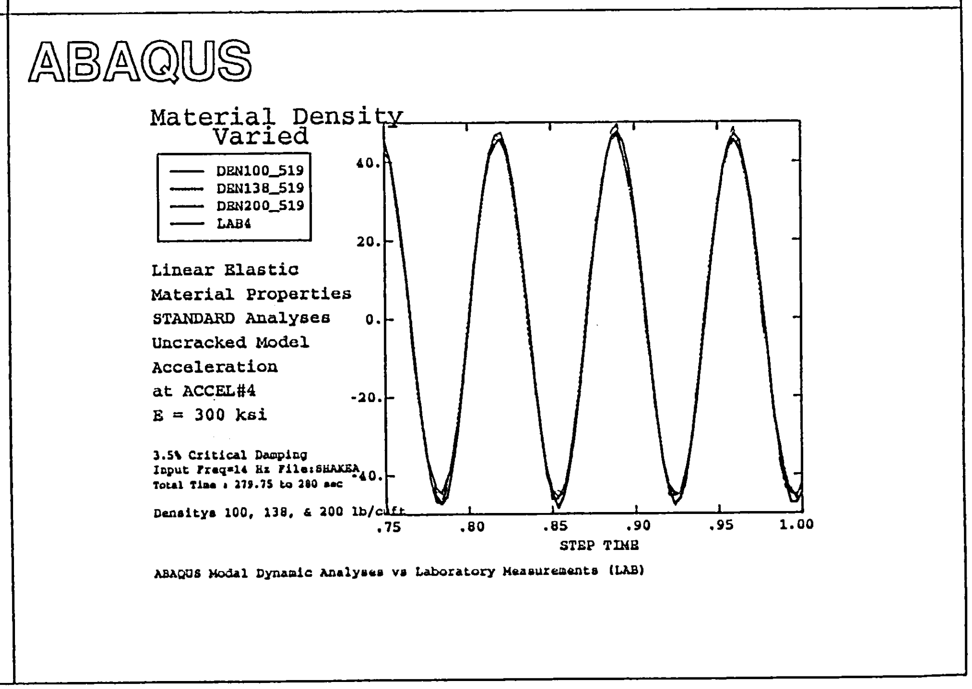
ABAQUS
Material Density Varied
DEN100_176
DEN138_176
DEN200_176
LAB7
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
E = 300 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
80.
40.
0.
-40.
-80.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)



ABAQUS
Material Density Varied
DEN100_204
DEN138_204
DEN200_204
LAB6
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
E = 300 ksi
3.5% Critical Damping
Input Freq=14 Hz Filename:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

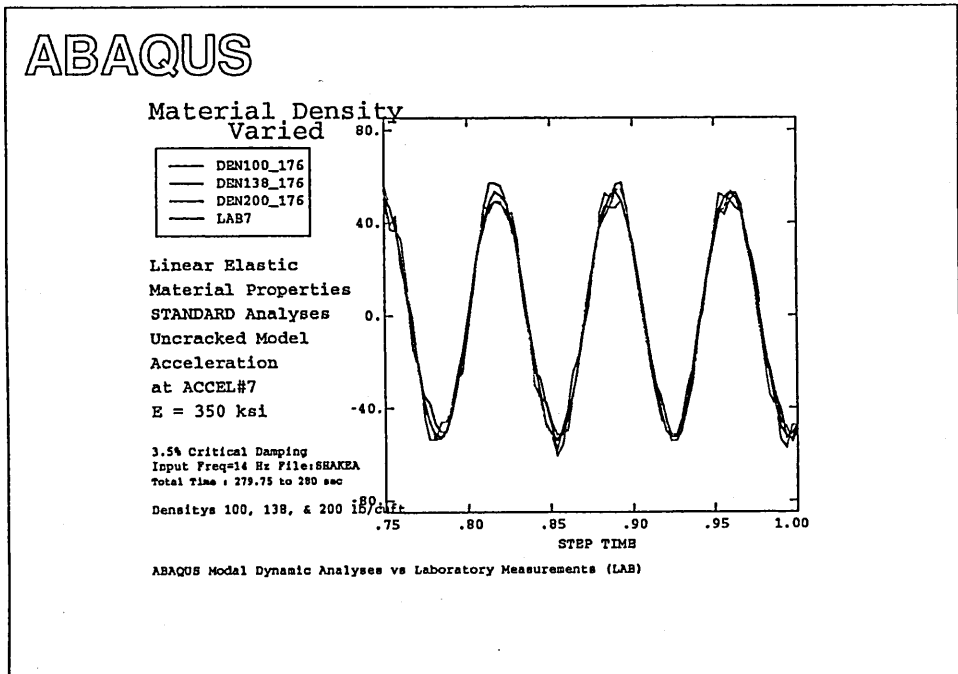


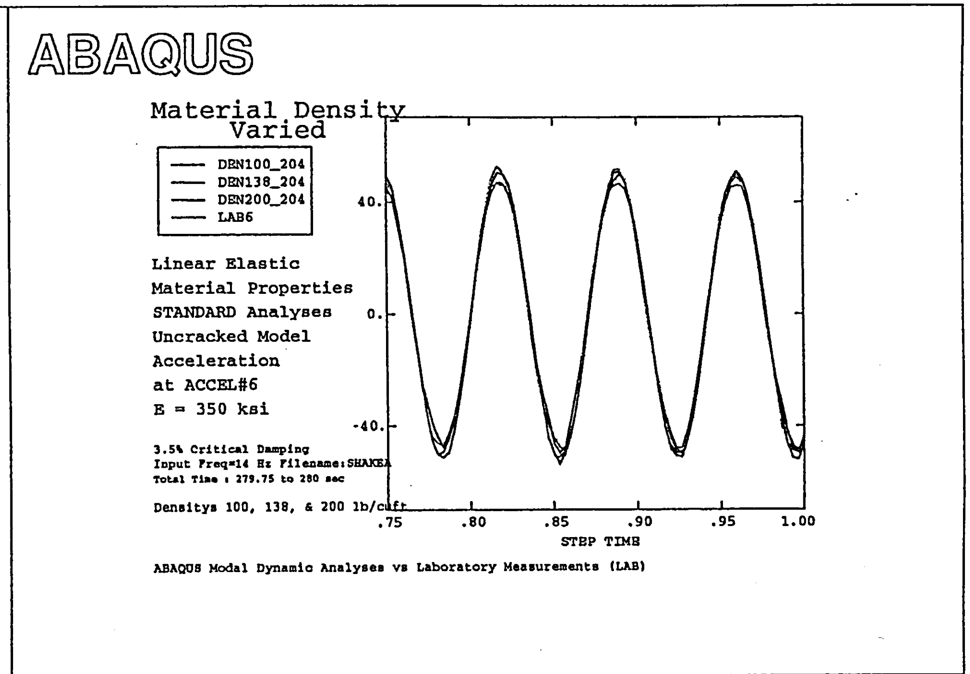
ABAQUS
Material Density Varied
DEN100_491
DEN138_491
DEN200_491
LAB5
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
E = 300 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 pcf
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

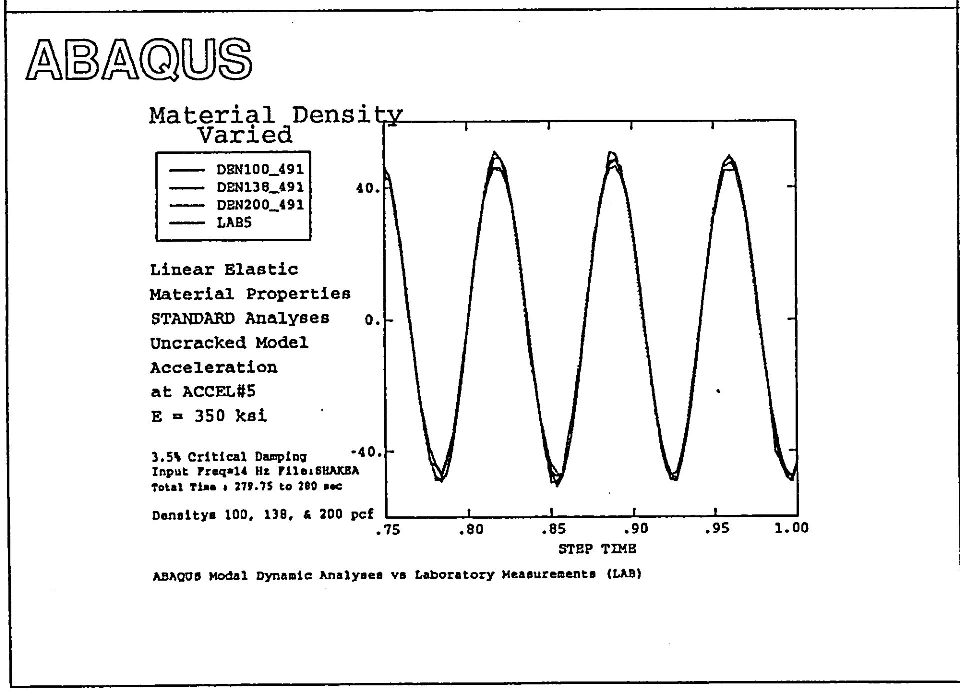


ABAQUS
Material Density Varied
DEN100_519
DEN138_519
DEN200_519
LAB4
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
E = 300 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
20.
0.
-20.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

Figure 950


ABAQUS
Material Density Varied
DEN100_176
DEN138_176
DEN200_176
LAB7
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
E = 350 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
80.
40.
0.
-40.
-80.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)


ABAQUS
Material Density Varied
DEN100_204
DEN138_204
DEN200_204
LAB6
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
E = 350 ksi
3.5% Critical Damping
Input Freq=14 Hz Filename:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)


ABAQUS
Material Density Varied
DEN100_491
DEN138_491
DEN200_491
LAB5
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
E = 350 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 pcf
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

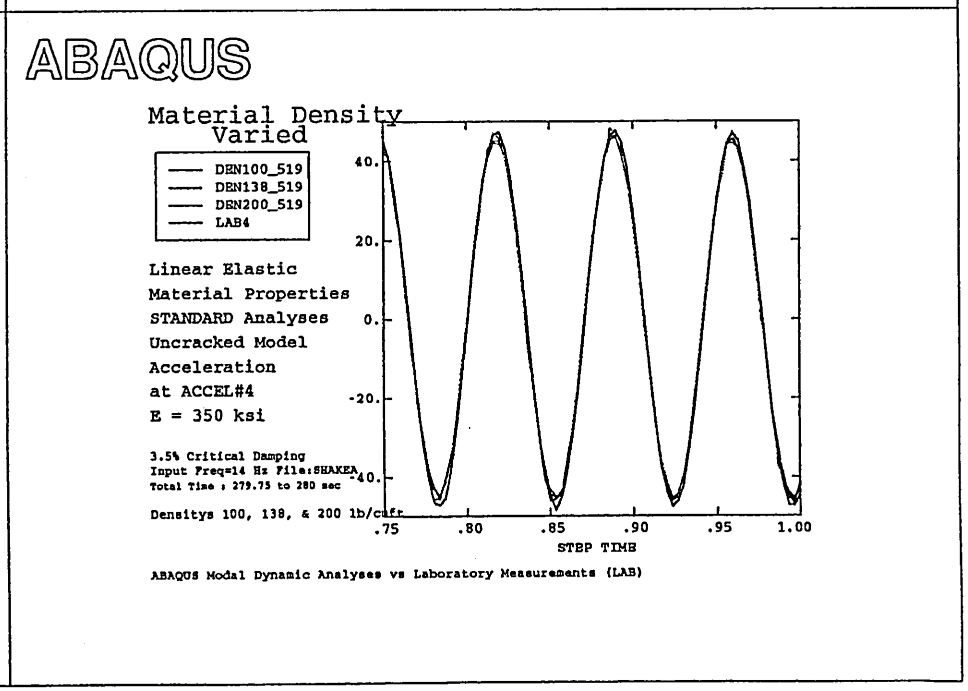

ABAQUS
Material Density Varied
DEN100_519
DEN138_519
DEN200_519
LAB4
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
E = 350 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
20.
0.
-20.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

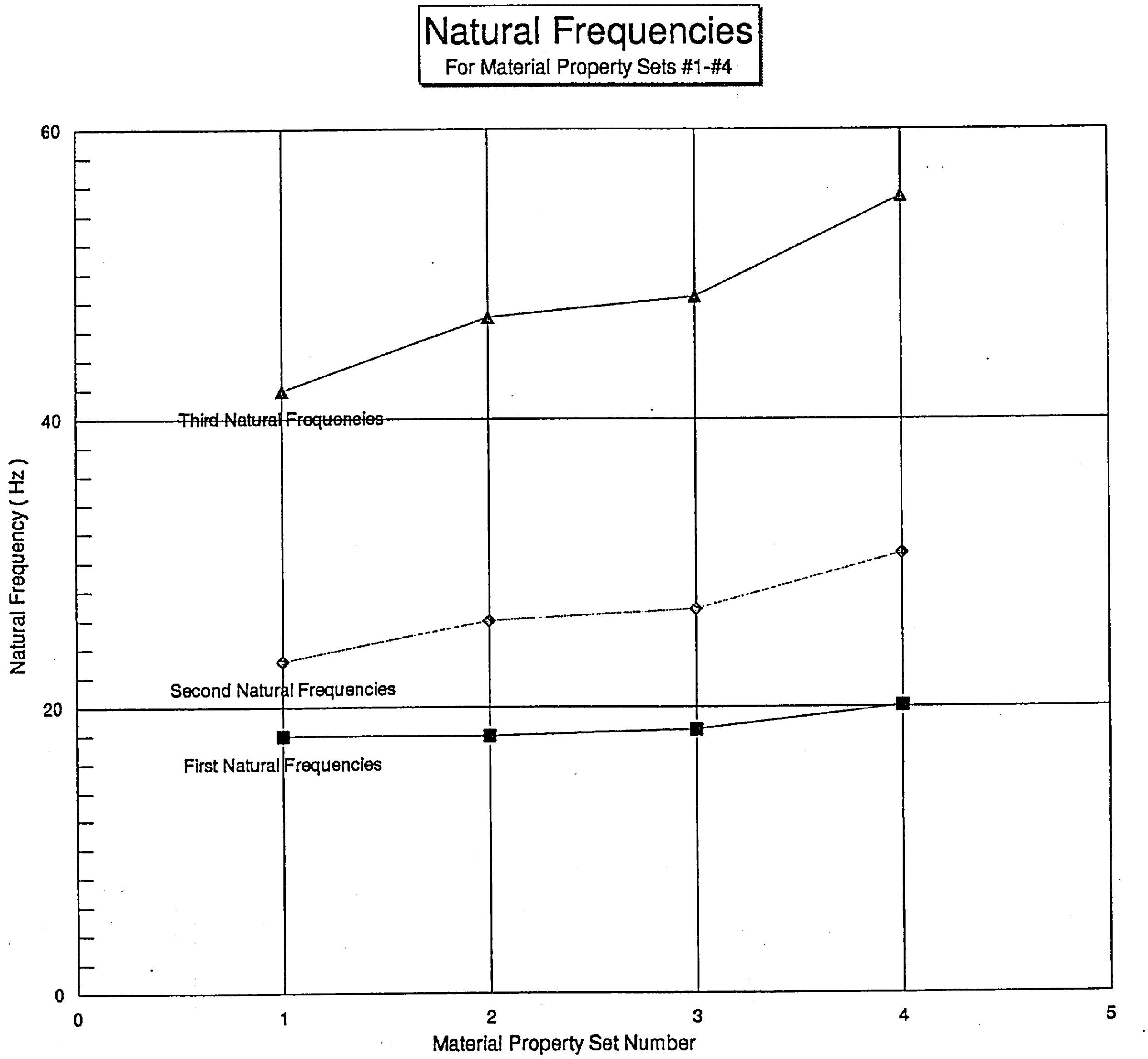
Figure g51

Appendix H : Sensitivity to the Amount and Method of Applying Damping in the ABAQUS Analyses

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3

Material Property Sets

Linear Elastic Material Property Set #1 : Elastic Modulus = 190 ksi; Material Density = 133 pcf
Linear Elastic Material Property Set #2 : Elastic Modulus = 200 ksi; Material Density = 140 pcf
Linear Elastic Material Property Set #3 : Elastic Modulus = 210 ksi; Material Density = 140 pcf
Linear Elastic Material Property Set #4 : Elastic Modulus = 250 ksi; Material Density = 140 pcf

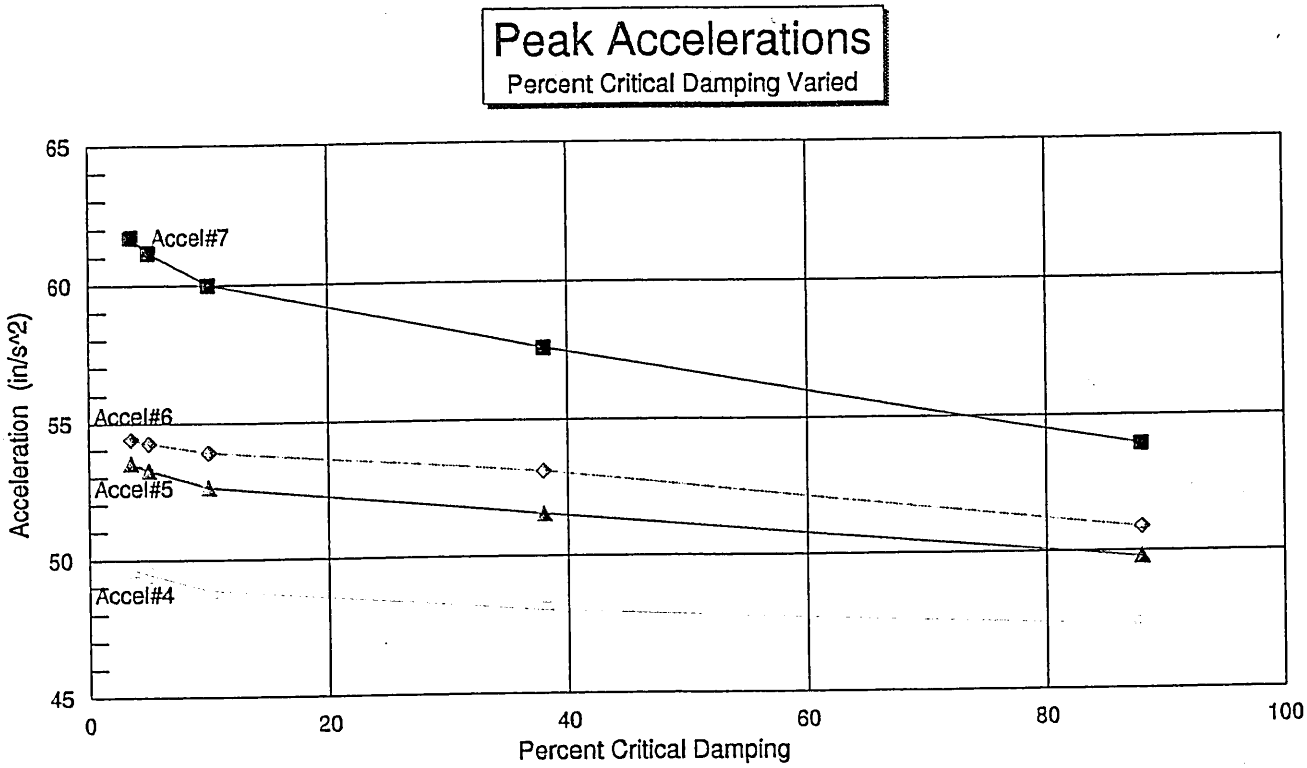


Natural Frequencies (Hz)					
Material Property Set #	1	2	3	4	LAB
Mode					
1	18.0	18.0	18.4	20.1	18.0
2	23.2	26.0	26.8	30.6	24.0
3	41.9	47.0	48.4	55.4	30.0

Figure h1

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%, 5%, 10%, 38% & 88%) critical

Linear Elastic Material Property Set #1 : Elastic Modulus = 190 ksi; Material Density = 133 pcf

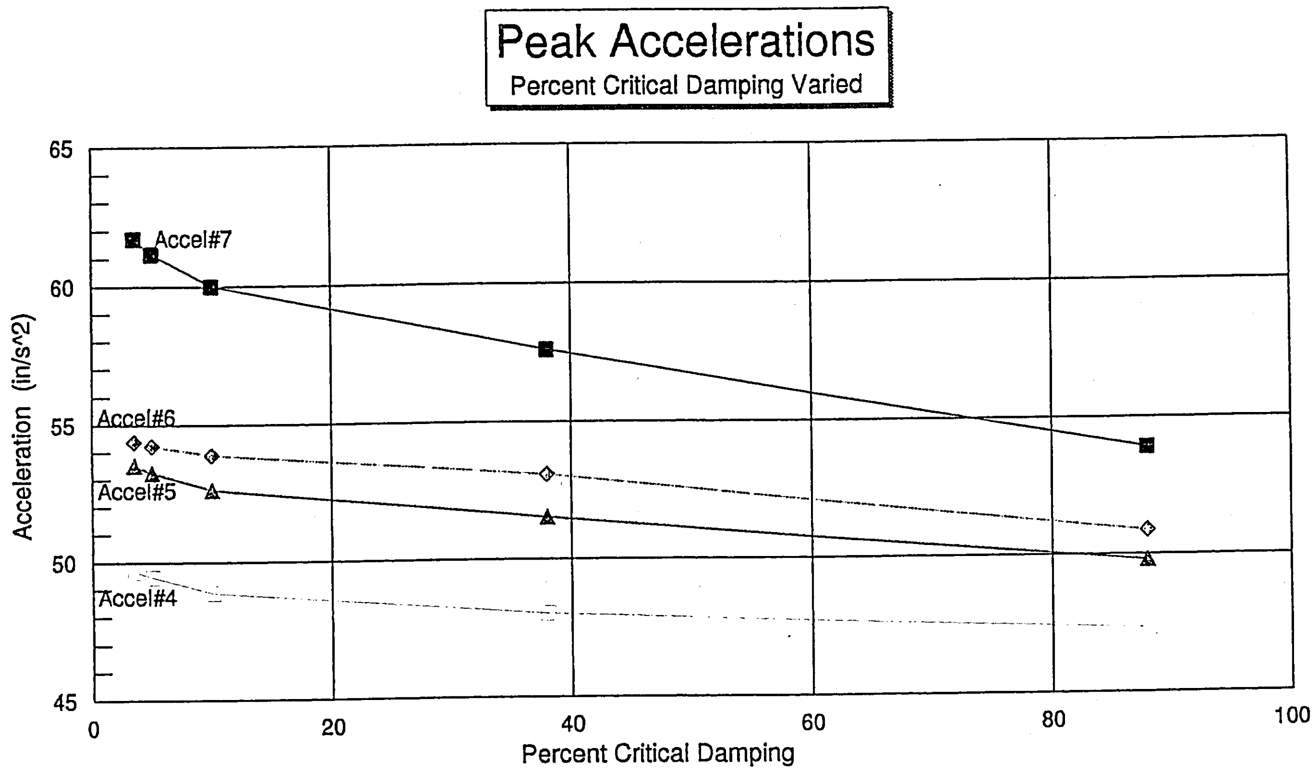


Peak Accelerations (inch / sec ^ 2)						
Percent Damping	3.5	5	10	38	88	LAB
Accel#7	61.73	61.17	59.99	57.60	53.90	53.26
Accel#6	54.39	54.23	53.88	53.07	50.87	51.72
Accel#5	53.52	53.25	52.61	51.53	49.80	49.26
Accel#4	49.66	49.44	48.87	48.04	47.32	47.72
CPU seconds	278.83	278.65	278.89	268.59	267.18	

Figure h2

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%, 5%, 10%, 38%, & 88%) critical

Linear Elastic Material Property Set #2 : Elastic Modulus = 200 ksi; Material Density = 140 pcf



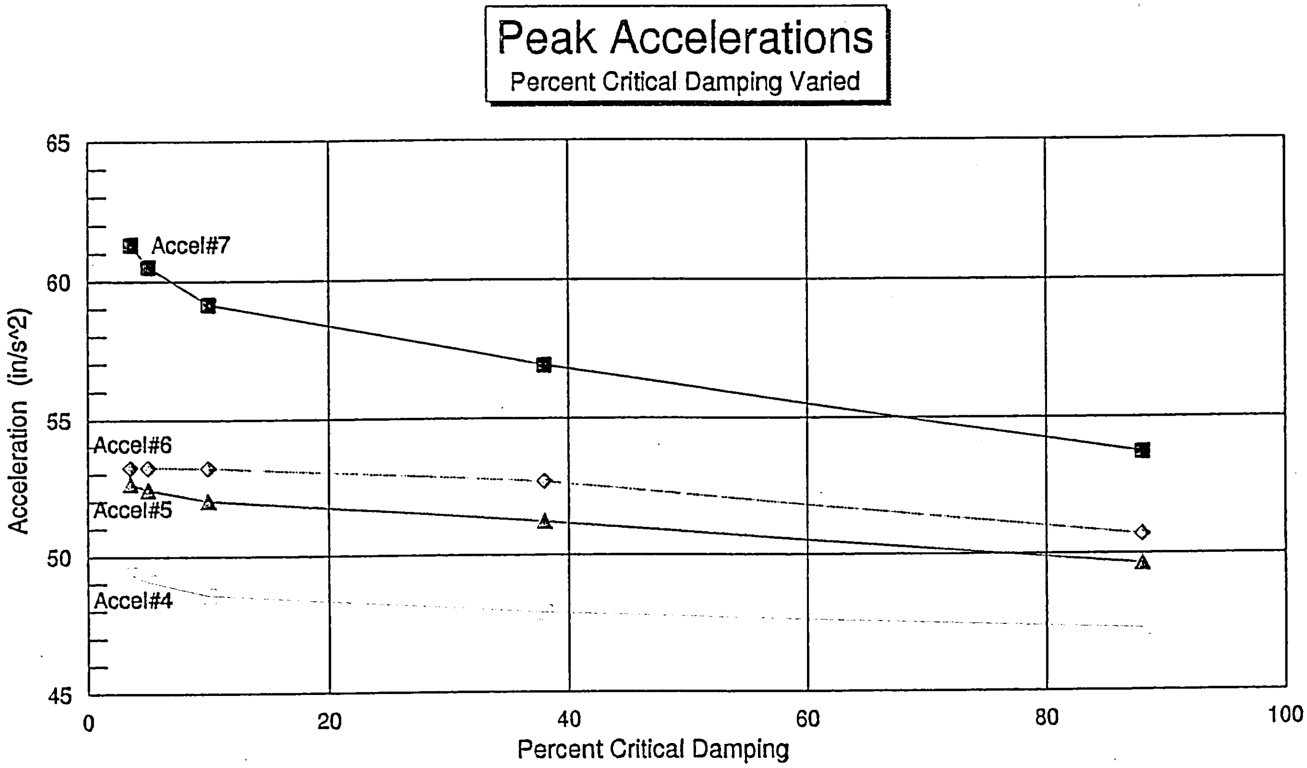
Peak Accelerations (inch / sec ^ 2)

Percent Damping	3.5	5	10	38	88	LAB
Accel#7	61.73	61.17	59.99	57.60	53.90	53.26
Accel#6	54.39	54.23	53.88	53.07	50.87	51.72
Accel#5	53.52	53.25	52.61	51.53	49.80	49.26
Accel#4	49.66	49.44	48.87	48.04	47.34	47.72

Figure h3

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%,5%,10%,38%,&88%) critical

Linear Elastic Material Property Set #3 : Elastic Modulus = 210 ksi; Material Density = 140 pcf

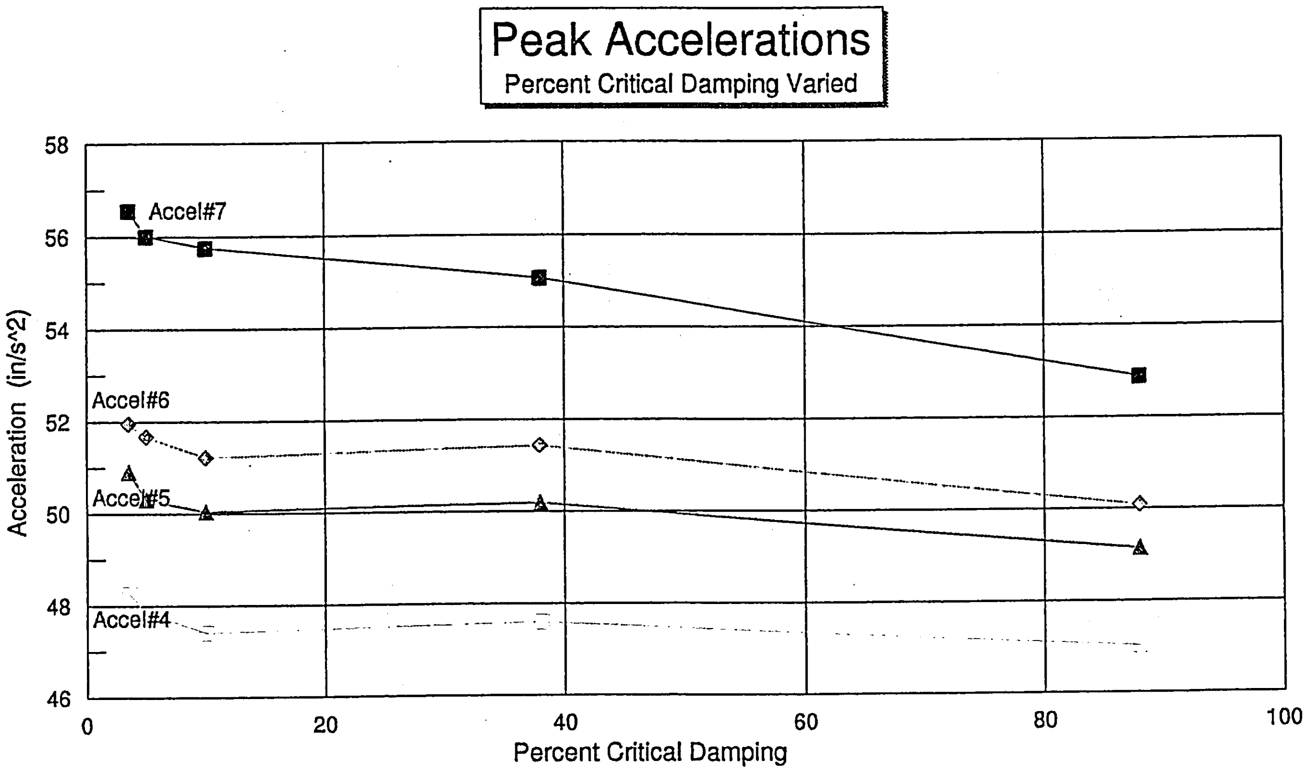


Peak Accelerations (inch / sec ^ 2)						
Percent Damping	3.5	5	10	38	88	LAB
Accel#7	61.31	60.51	59.15	56.91	53.68	53.26
Accel#6	53.22	53.23	53.21	52.67	50.70	51.72
Accel#5	52.65	52.43	52.02	51.21	49.65	49.26
Accel#4	49.36	49.06	48.57	47.90	47.27	47.72

Figure h4

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%, 5%, 10%, 38% & 88%) critical

Linear Elastic Material Property Set #4 : Elastic Modulus = 250 ksi; Material Density = 140 pcf



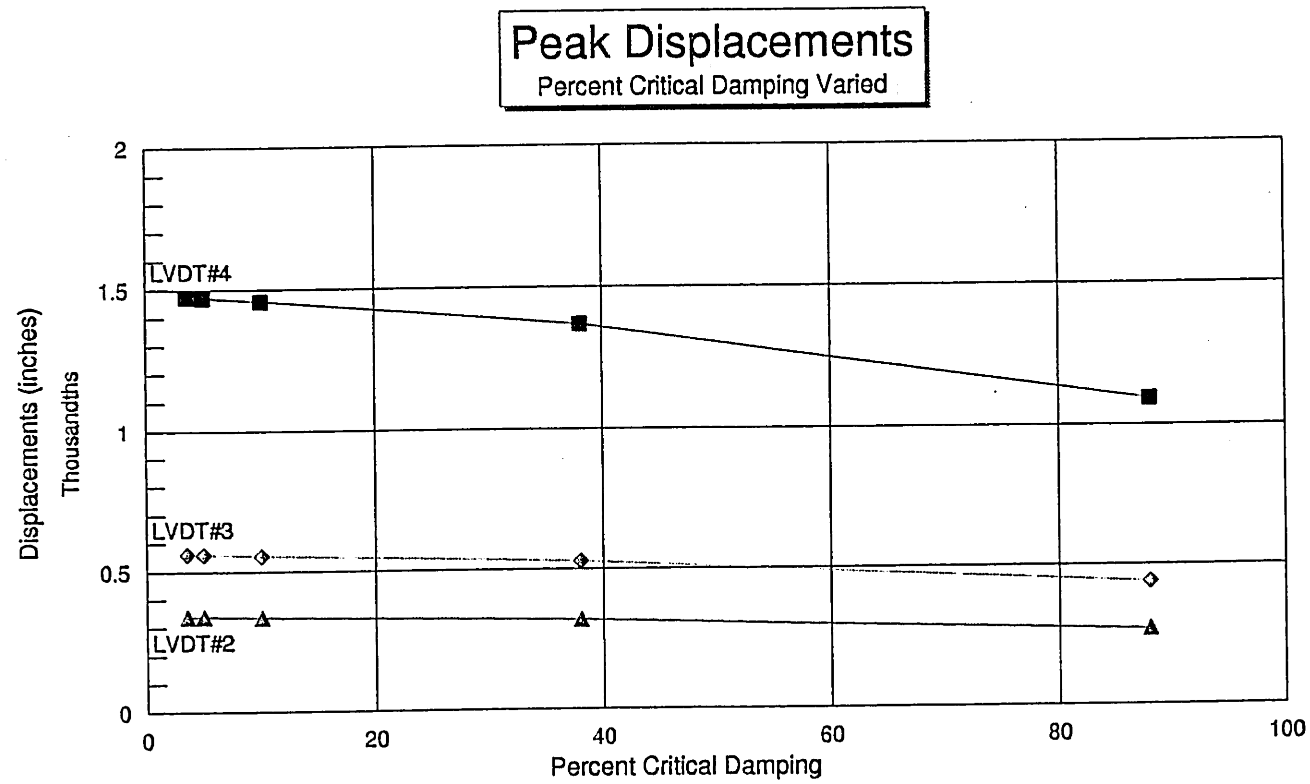
Peak Accelerations (inch / sec ^ 2)

Percent Damping	3.5	5	10	38	88	LAB
Accel#7	56.56	56.01	55.76	55.07	52.87	53.26
Accel#6	51.95	51.67	51.22	51.43	50.09	51.72
Accel#5	50.90	50.30	50.04	50.19	49.14	49.26
Accel#4	48.26	47.84	47.41	47.60	47.03	47.72

Figure h5

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%,5%,10%,38%,&88%) critical

Linear Elastic Material Property Set #1 : Elastic Modulus = 190 ksi; Material Density = 133 pcf

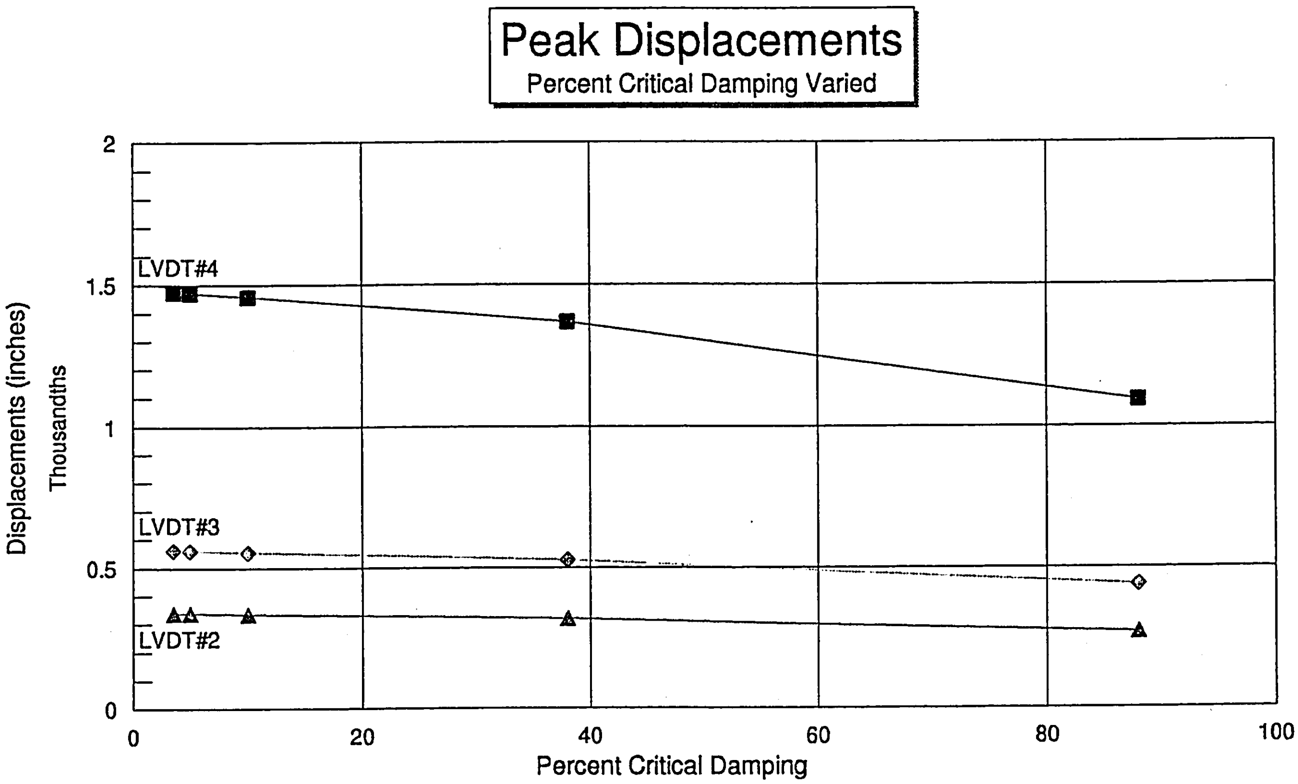


Peak Displacements (inches)						
Percent Damping	3.5	5	10	38	88	LAB
LVDT#4 LVDT#3 LVDT#2	1.5E-03 5.6E-04 3.4E-04	1.5E-03 5.6E-04 3.4E-04	1.5E-03 5.5E-04 3.3E-04	1.4E-03 5.3E-04 3.2E-04	1.1E-03 4.4E-04 2.7E-04	7.8E-04 3.0E-04 1.8E-04
CPU seconds	278.83	278.65	278.89	268.59	267.18	

Figure h6

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%,5%,10%,38%,&88%) critical

Linear Elastic Material Property Set #2 : Elastic Modulus = 200 ksi; Material Density = 140 pcf



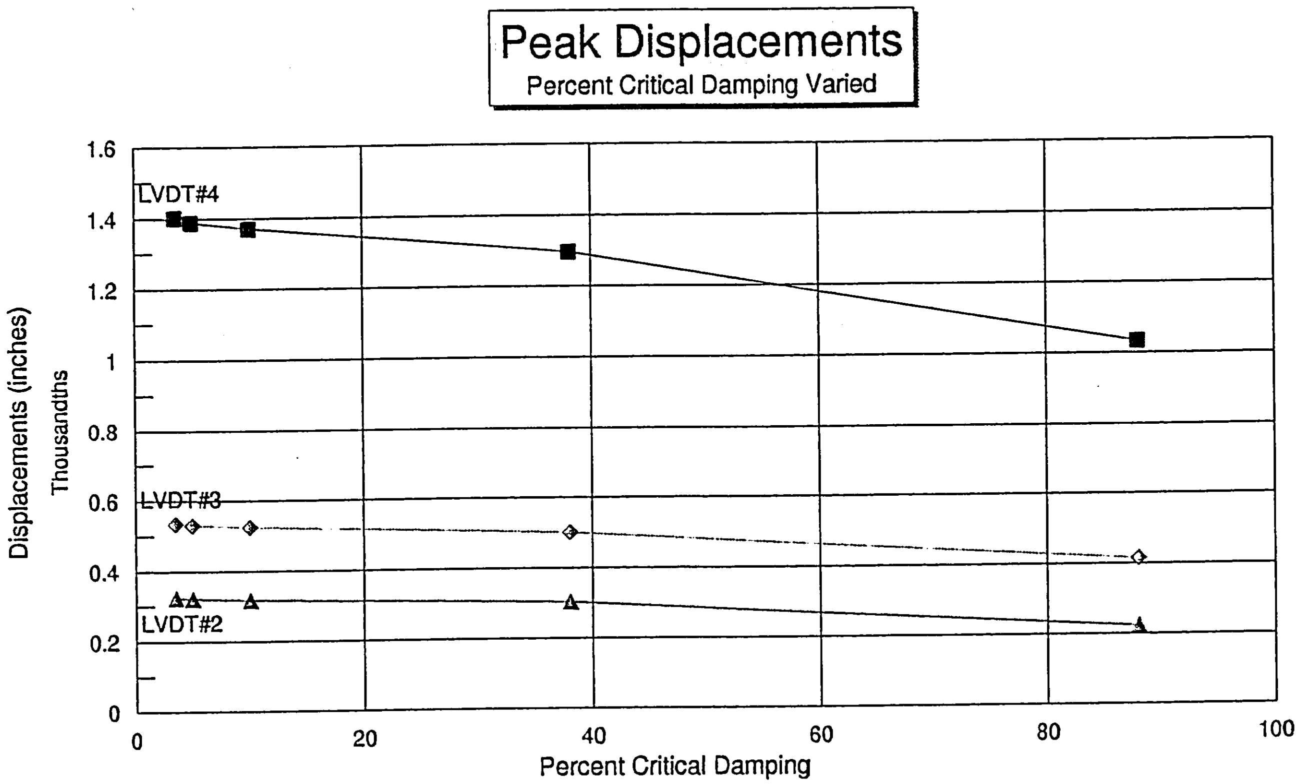
Peak Displacements (inches)

Percent Damping	3.5	5	10	38	88	LAB
LVDT#4	1.5E-03	1.5E-03	1.5E-03	1.4E-03	1.1E-03	7.8E-04
LVDT#3	5.6E-04	5.6E-04	5.5E-04	5.3E-04	4.4E-04	3.0E-04
LVDT#2	3.4E-04	3.4E-04	3.3E-04	3.2E-04	2.7E-04	1.8E-04

Figure h7

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%,5%,10%,38%,&88%) critical

Linear Elastic Material Property Set #3 : Elastic Modulus = 210 ksi; Material Density = 140 pcf



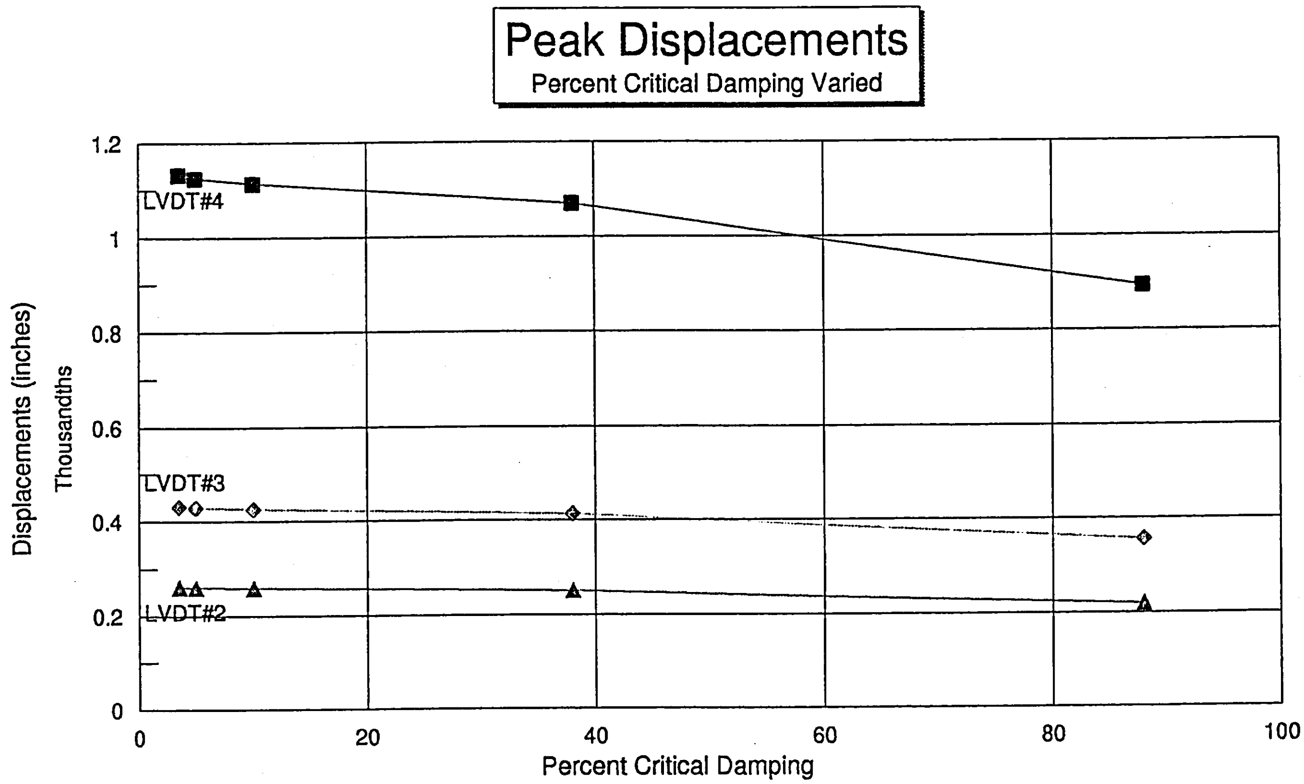
Peak Displacements (inches)

Percent Damping	3.5	5	10	38	88	LAB
LVDT#4	1.4E-03	1.4E-03	1.4E-03	1.3E-03	1.0E-03	7.8E-04
LVDT#3	5.3E-04	5.3E-04	5.2E-04	5.0E-04	4.1E-04	3.0E-04
LVDT#2	3.2E-04	3.2E-04	3.2E-04	3.0E-04	2.2E-04	1.8E-04

Figure h8

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%,5%,10%,38%,&88%) critical

Linear Elastic Material Property Set #4 : Elastic Modulus = 250 ksi; Material Density = 140 pcf



Peak Displacements (inches)						
Percent Damping	3.5	5	10	38	88	LAB
LVDT#4	1.1E-03	1.1E-03	1.1E-03	1.1E-03	8.9E-04	7.8E-04
LVDT#3	4.3E-04	4.3E-04	4.3E-04	4.1E-04	3.6E-04	3.0E-04
LVDT#2	2.6E-04	2.6E-04	2.6E-04	2.5E-04	2.2E-04	1.8E-04

Figure h9

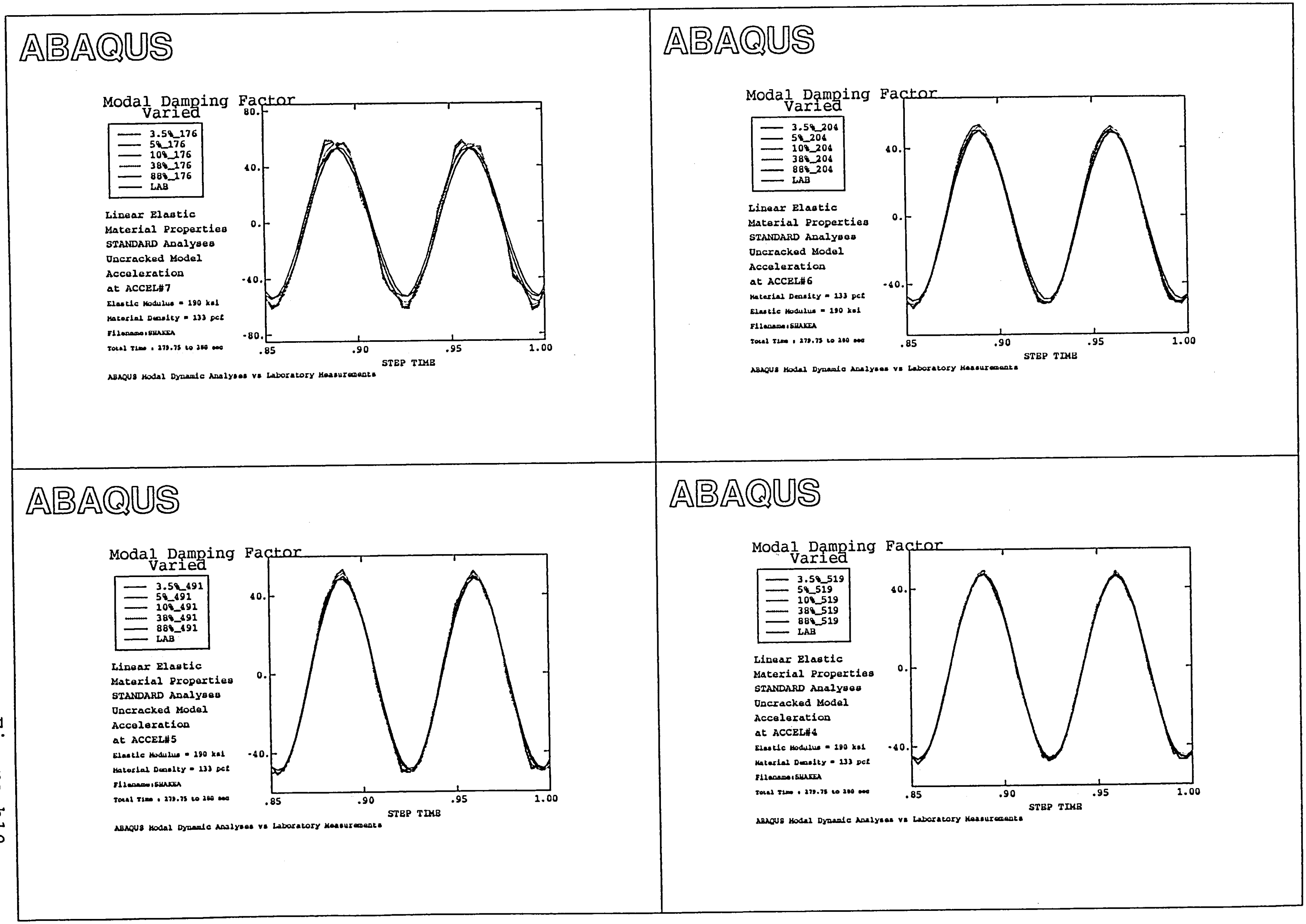
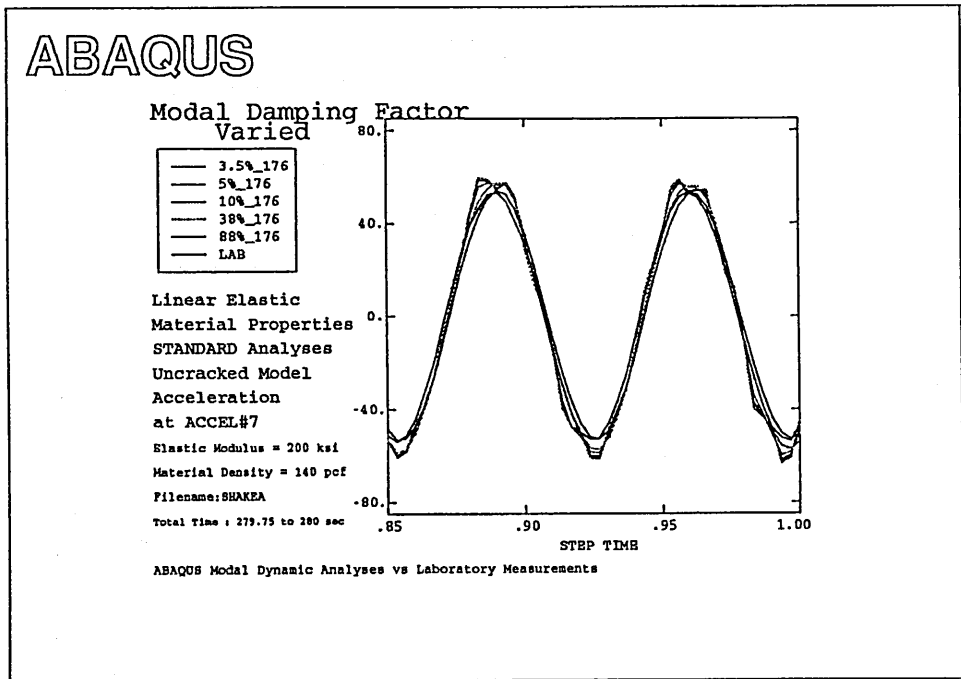
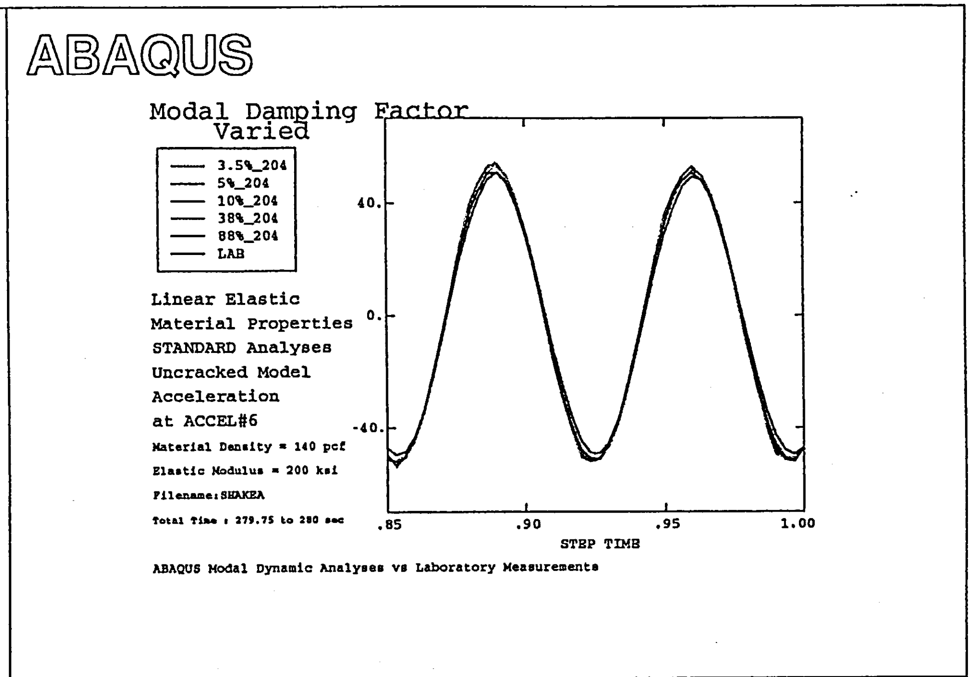
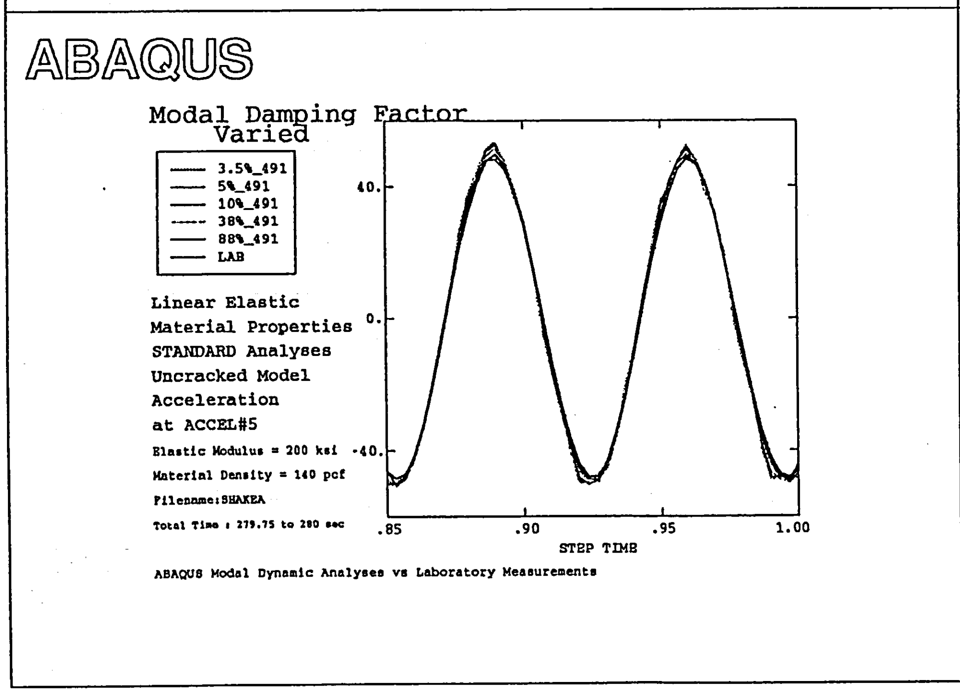

ABAQUS
Modal Damping Factor Varied
3.5%_176
5%_176
10%_176
38%_176
88%_176
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Elastic Modulus = 190 ksi
Material Density = 133 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements
ABAQUS
Modal Damping Factor Varied
3.5%_204
5%_204
10%_204
38%_204
88%_204
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Material Density = 133 pcf
Elastic Modulus = 190 ksi
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements
ABAQUS
Modal Damping Factor Varied
3.5%_491
5%_491
10%_491
38%_491
88%_491
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Elastic Modulus = 190 ksi
Material Density = 133 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements
ABAQUS
Modal Damping Factor Varied
3.5%_519
5%_519
10%_519
38%_519
88%_519
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Elastic Modulus = 190 ksi
Material Density = 133 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

Figure h10


ABAQUS
Modal Damping Factor
Varied
3.5%_176
5%_176
10%_176
38%_176
88%_176
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Elastic Modulus = 200 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements


ABAQUS
Modal Damping Factor
Varied
3.5%_204
5%_204
10%_204
38%_204
88%_204
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Material Density = 140 pcf
Elastic Modulus = 200 ksi
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements


ABAQUS
Modal Damping Factor
Varied
3.5%_491
5%_491
10%_491
38%_491
88%_491
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Elastic Modulus = 200 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

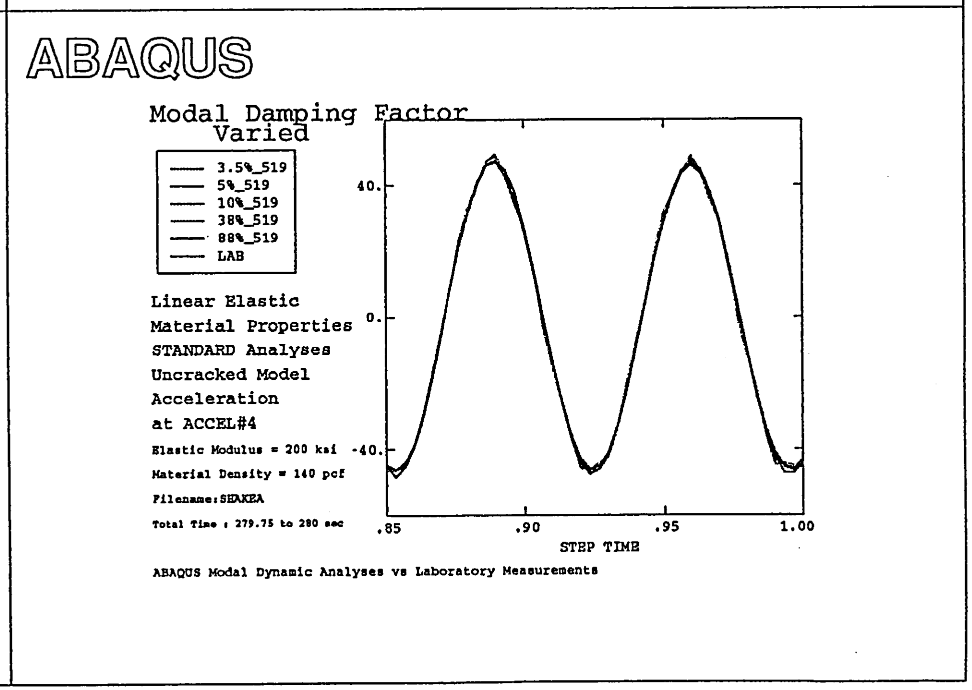
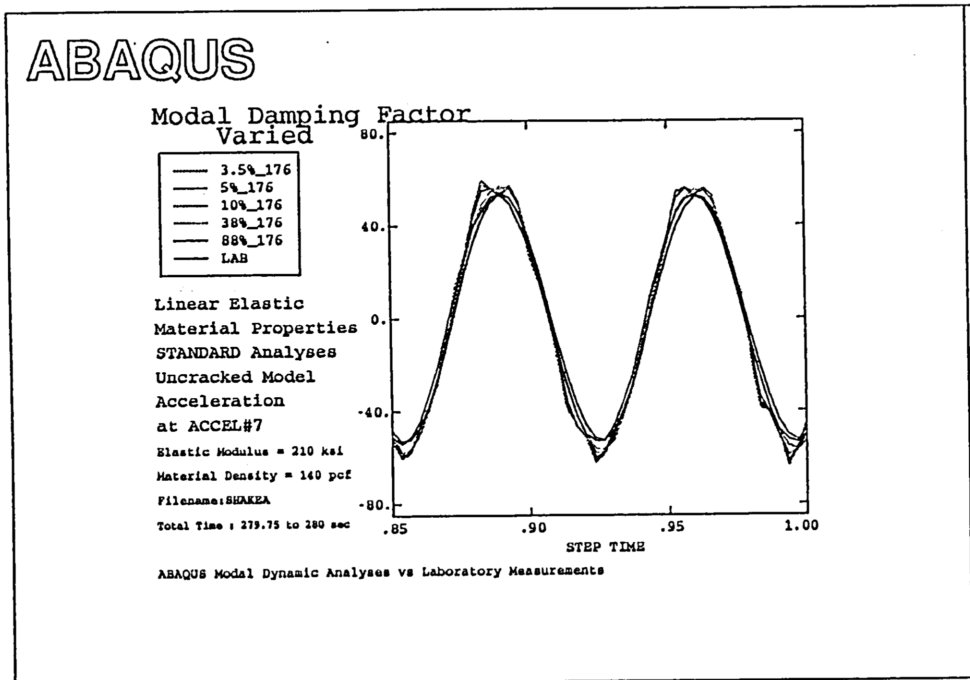
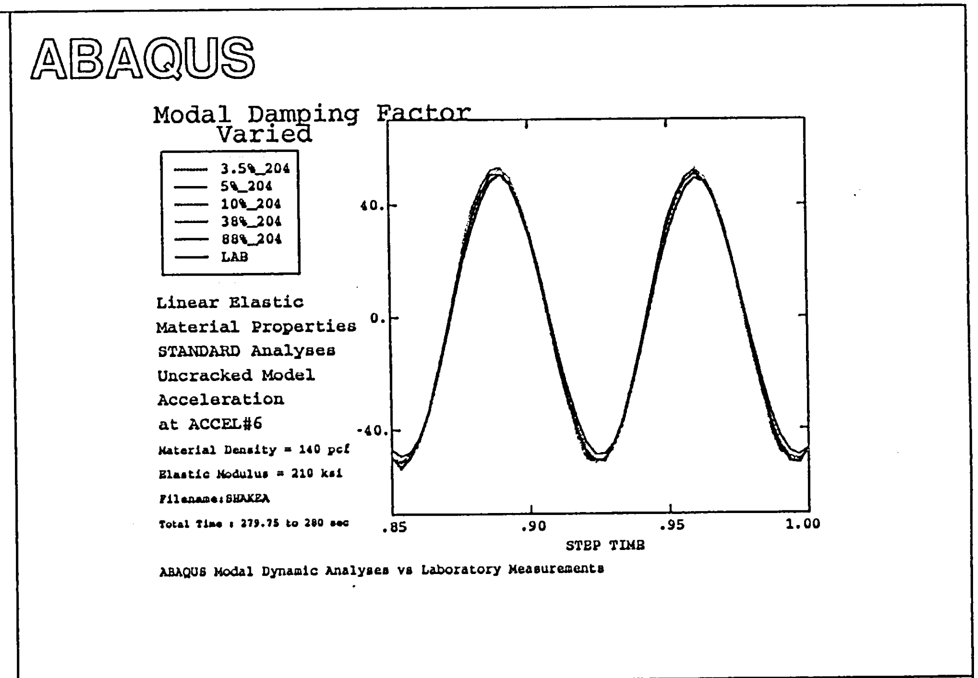
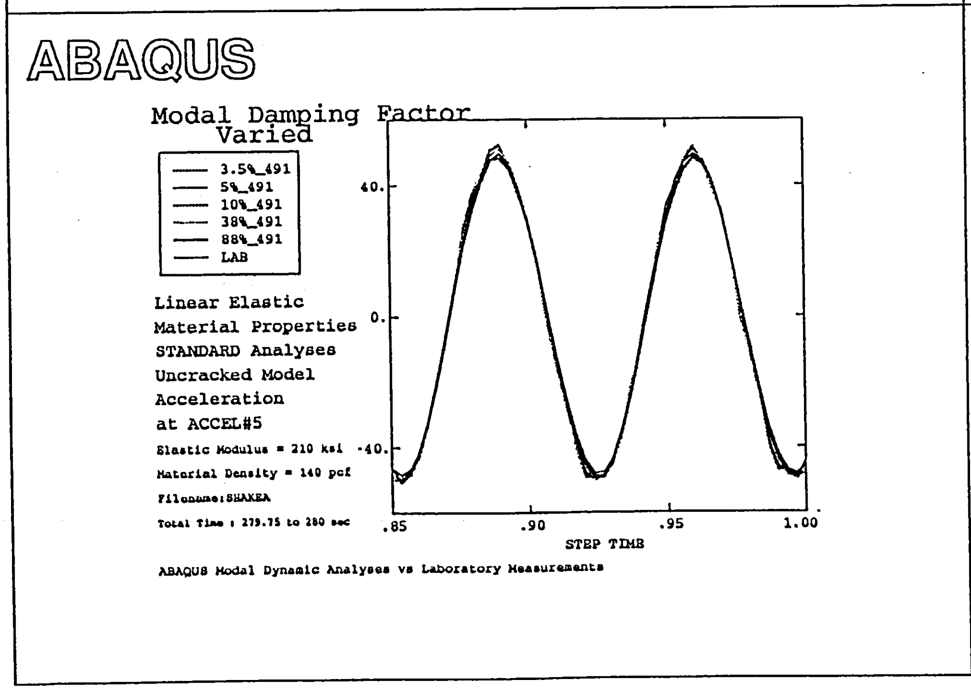

ABAQUS
Modal Damping Factor
Varied
3.5%_519
5%_519
10%_519
38%_519
88%_519
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Elastic Modulus = 200 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

Figure h11


ABAQUS
Modal Damping Factor
Varied
3.5%_176
5%_176
10%_176
38%_176
88%_176
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Elastic Modulus = 210 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements


ABAQUS
Modal Damping Factor
Varied
3.5%_204
5%_204
10%_204
38%_204
88%_204
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements


ABAQUS
Modal Damping Factor
Varied
3.5%_491
5%_491
10%_491
38%_491
88%_491
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Elastic Modulus = 210 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

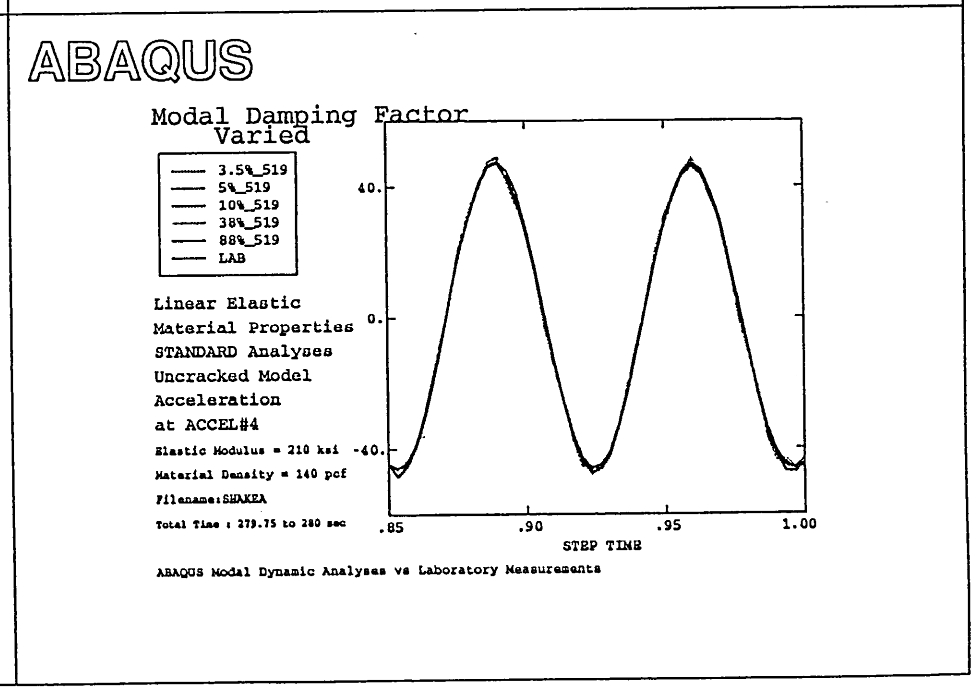
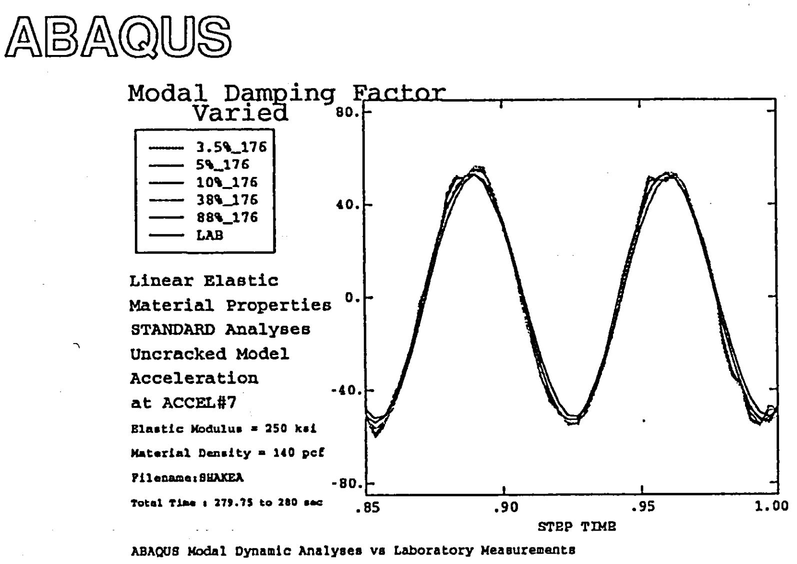
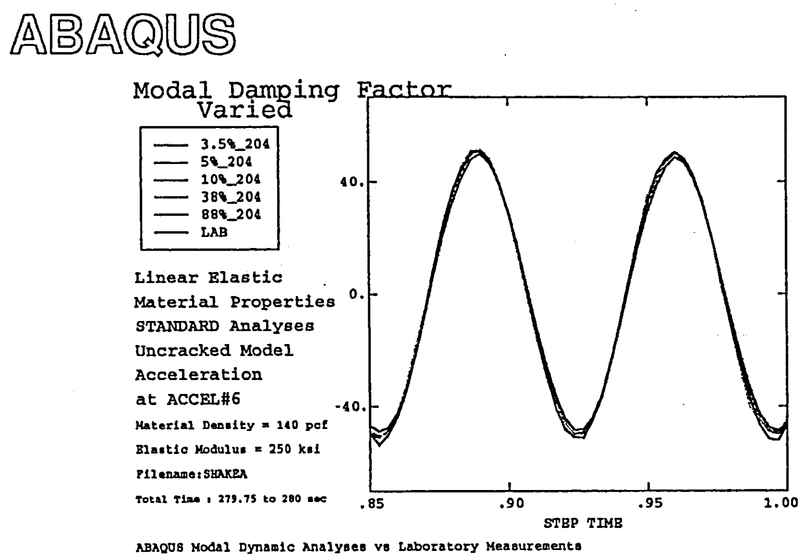
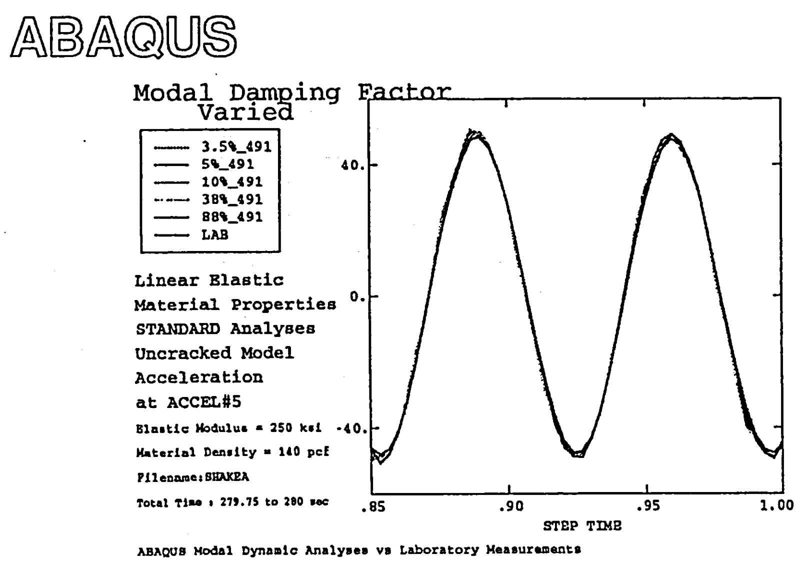

ABAQUS
Modal Damping Factor
Varied
3.5%_519
5%_519
10%_519
38%_519
88%_519
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Elastic Modulus = 210 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

Figure h12


ABAQUS
Modal Damping Factor Varied
3.5%_176
5%_176
10%_176
38%_176
88%_176
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Elastic Modulus = 250 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements


ABAQUS
Modal Damping Factor Varied
3.5%_204
5%_204
10%_204
38%_204
88%_204
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Material Density = 140 pcf
Elastic Modulus = 250 ksi
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements


ABAQUS
Modal Damping Factor Varied
3.5%_491
5%_491
10%_491
38%_491
88%_491
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Elastic Modulus = 250 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

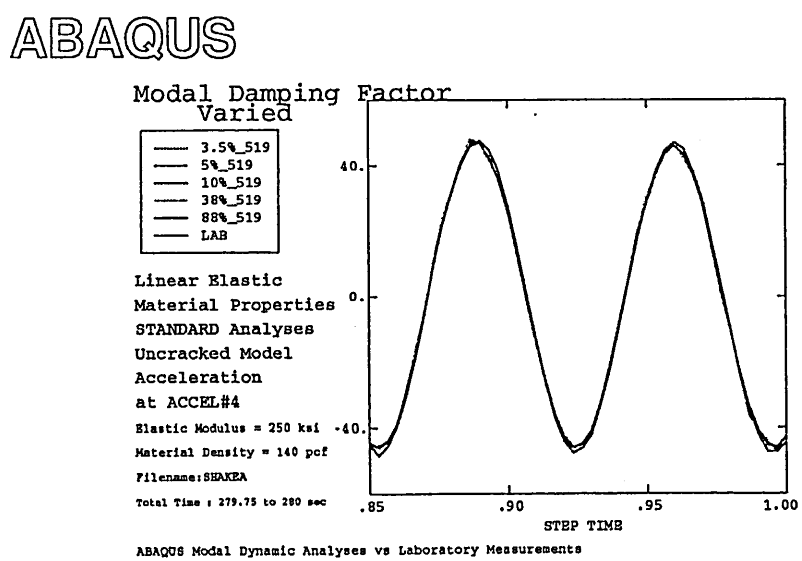

ABAQUS
Modal Damping Factor Varied
3.5%_519
5%_519
10%_519
38%_519
88%_519
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Elastic Modulus = 250 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

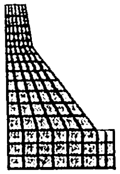
Figure h13

ABAQUS

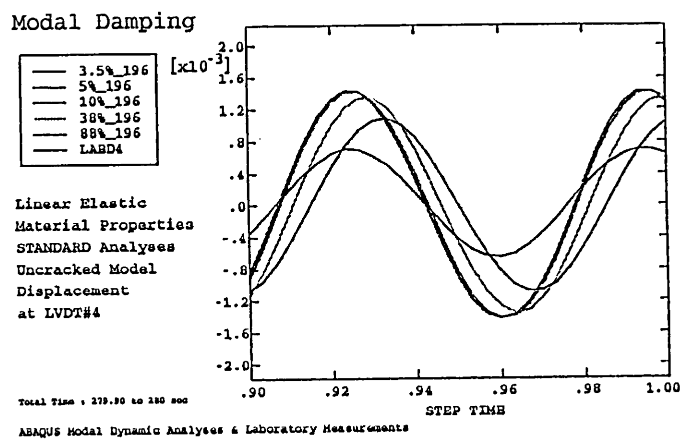
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Modal Damping

Comparison of Displacements
ABAQUS STANDARD
Modal Dynamic Analysis

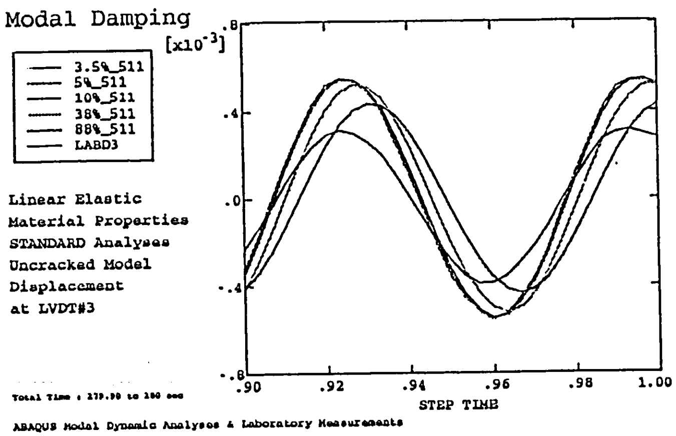
Input Record SHAKEA
Elastic Modulus = 190 ksi
Density = 133.0 pcf
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

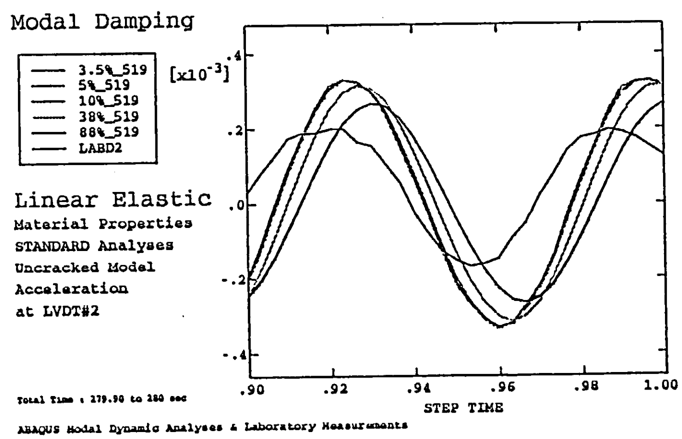
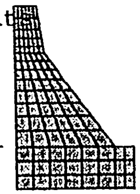


Figure h14

ABAQUS

Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Modal Damping

Comparison of Displacements
ABAQUS STANDARD
Modal Dynamic Analysis



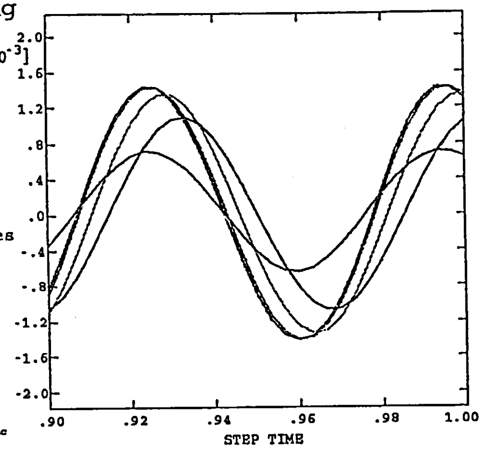
Input Record SHAKEA
Elastic Modulus = 200 ksi
Density = 140.0 pcf
Mesh # 3

ABAQUS

Modal Damping

3.5%_196
5%_196
10%_196
38%_196
88%_196
LABD4

Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Displacement
at LVDT#4



Total Time : 279.90 to 280 sec

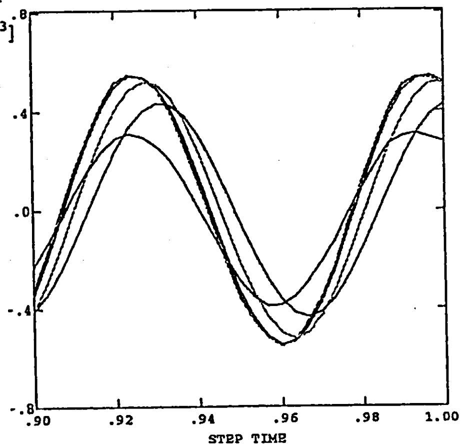
ABAQUS Modal Dynamic Analyses & Laboratory Measurements

ABAQUS

Modal Damping

3.5%_511
5%_511
10%_511
38%_511
88%_511
LABD3

Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Displacement
at LVDT#3



Total Time : 279.90 to 280 sec

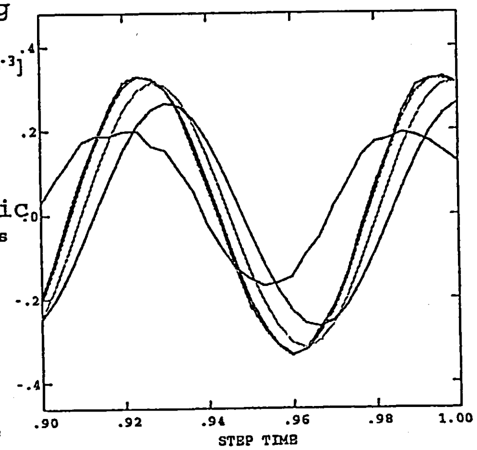
ABAQUS Modal Dynamic Analyses & Laboratory Measurements

ABAQUS

Modal Damping

3.5%_519
5%_519
10%_519
38%_519
88%_519
LABD2

Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at LVDT#2



Total Time : 279.90 to 280 sec

ABAQUS Modal Dynamic Analyses & Laboratory Measurements

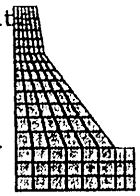
Figure h15

ABAQUS

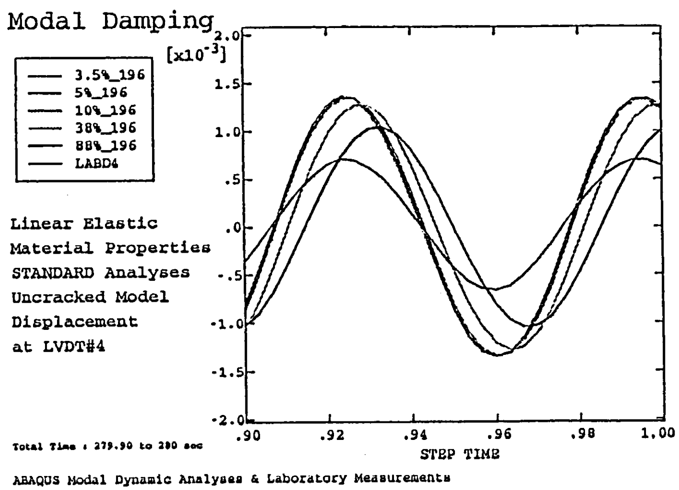
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Modal Damping

Comparison of Displacement
ABAQUS STANDARD
Modal Dynamic Analysis

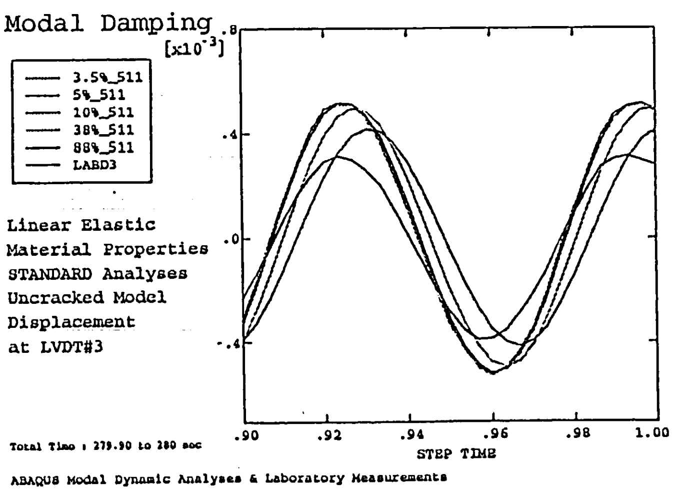
Input Record SHAKEA
Elastic Modulus = 210 ksi
Density = 140.0 pcf
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

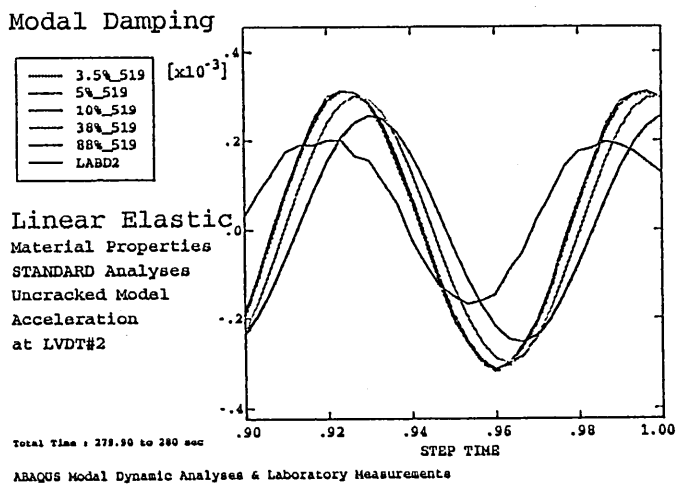


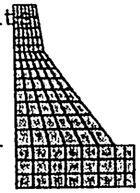
Figure h16

ABAQUS

Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Modal Damping

Comparison of Displacements
ABAQUS STANDARD
Modal Dynamic Analysis

Input Record SHAKEA
Elastic Modulus = 250 ksi
Density = 140.0 pcf
Mesh # 3

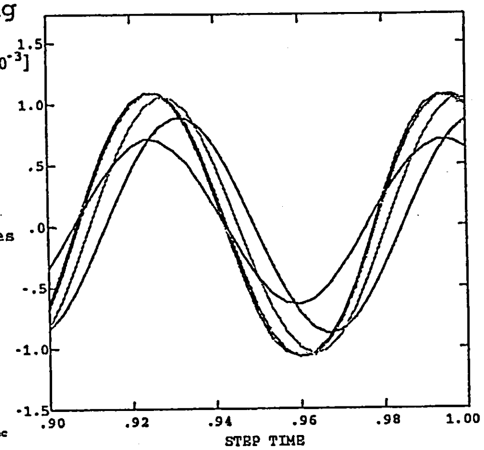


ABAQUS

Modal Damping

3.5%_196
5%_196
10%_196
38%_196
88%_196
LABD4

Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Displacement
at LVDT#4



Total Time : 279.90 to 280 sec

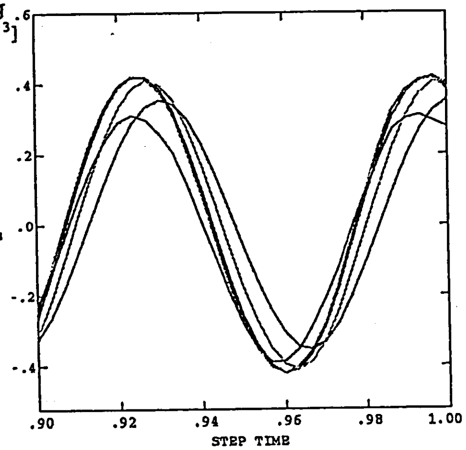
ABAQUS Modal Dynamic Analyses & Laboratory Measurements

ABAQUS

Modal Damping

3.5%_511
5%_511
10%_511
38%_511
88%_511
LABD3

Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Displacement
at LVDT#3



Total Time : 279.90 to 280 sec

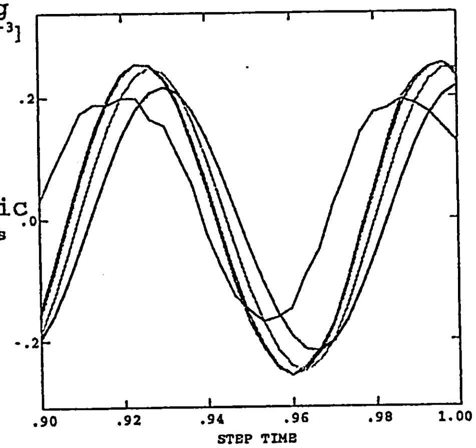
ABAQUS Modal Dynamic Analyses & Laboratory Measurements

ABAQUS

Modal Damping

3.5%_519
5%_519
10%_519
38%_519
88%_519
LABD2

Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at LVDT#2



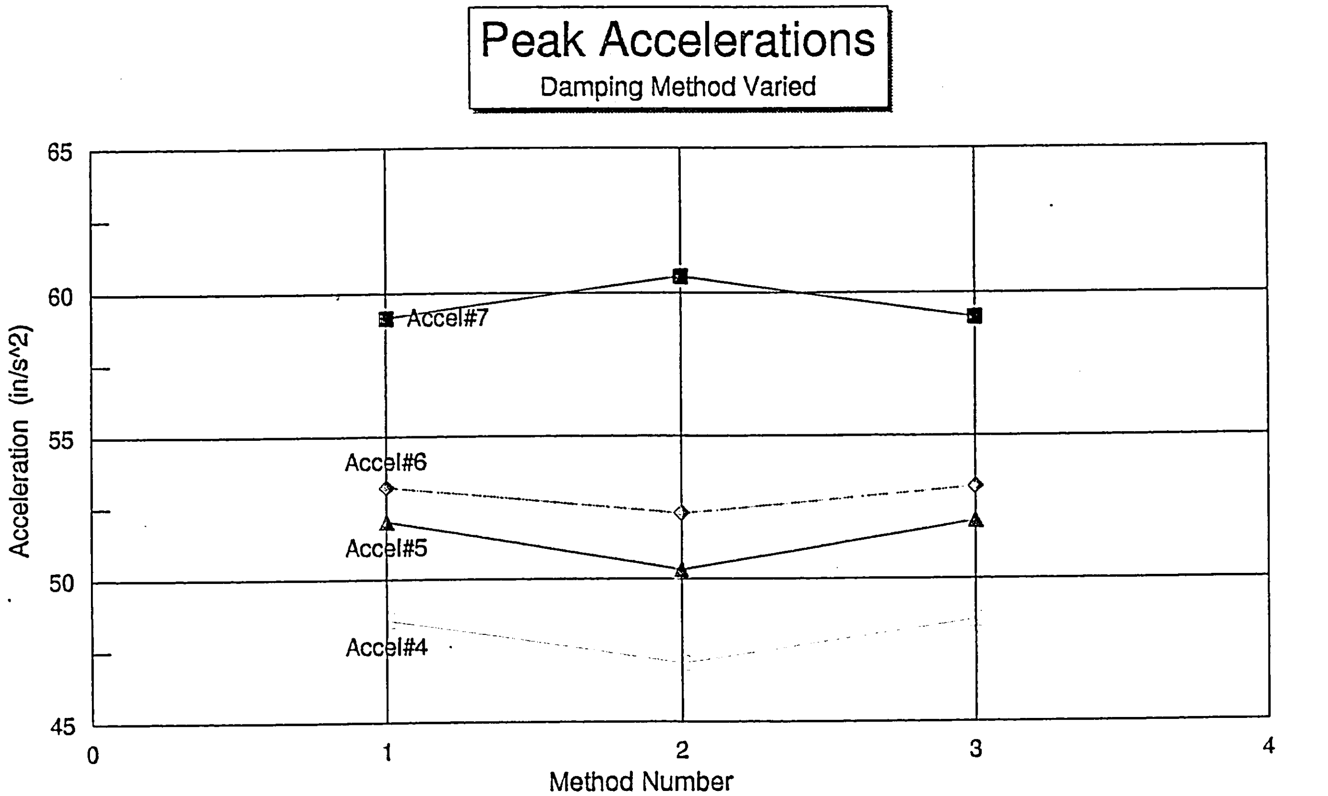
Total Time : 279.90 to 280 sec

ABAQUS Modal Dynamic Analyses & Laboratory Measurements

Figure h17

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Damping Method
Mesh#3
Modal Damping; Rayleigh Damping; Composite Damping
10 Percent of Critical Damping

Elastic Modulus = 210 ksi; Material Density = 138.2 pcf

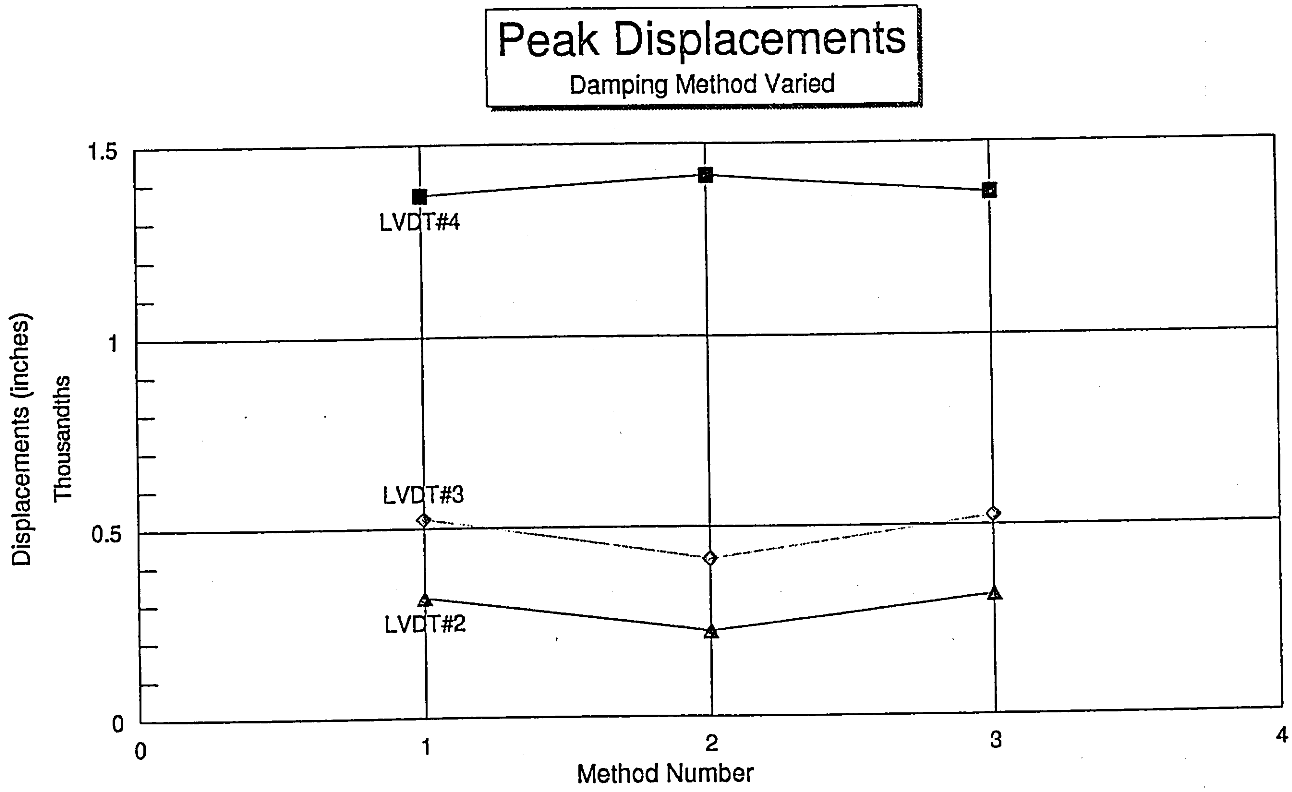


Peak Accelerations (inch / sec ^ 2)				
	Modal	Rayleigh	Composite	
Method Number	1	2	3	LAB
Accel#7	59.15	60.57	59.15	53.26
Accel#6	53.21	52.29	53.21	51.72
Accel#5	52.02	50.31	52.02	49.26
Accel#4	48.57	47.06	48.57	47.72
CPU TIME (SEC)	264	264	263	

Figure h18

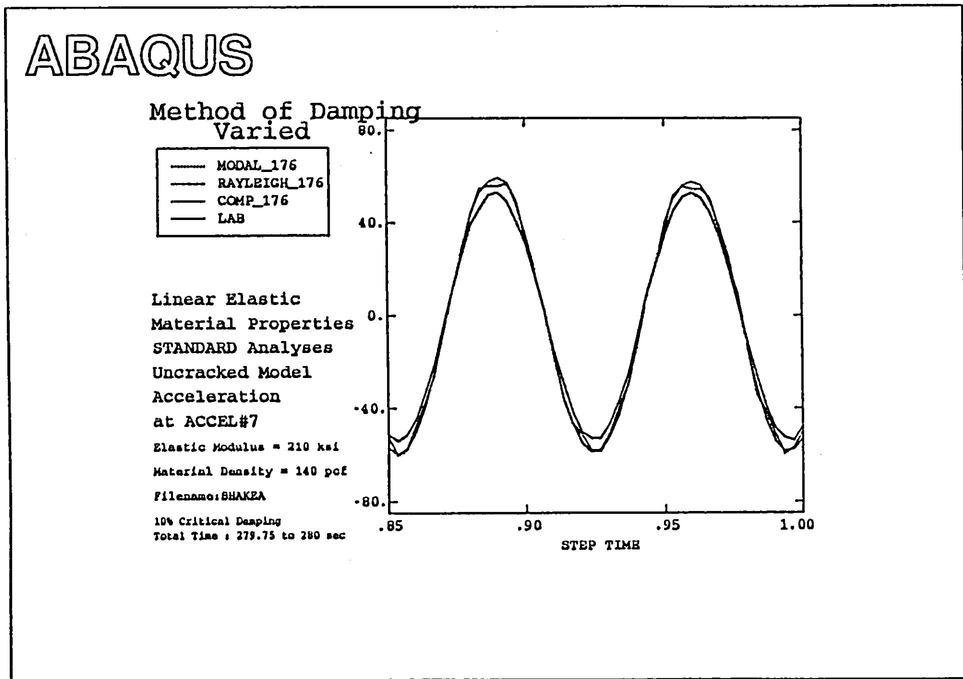
Uncracked Koyna Laboratory Study
Sensitivity to Variation in Damping Method
Mesh#3
Modal Damping; Rayleigh Damping; Composite Damping
10 Percent of Critical Damping

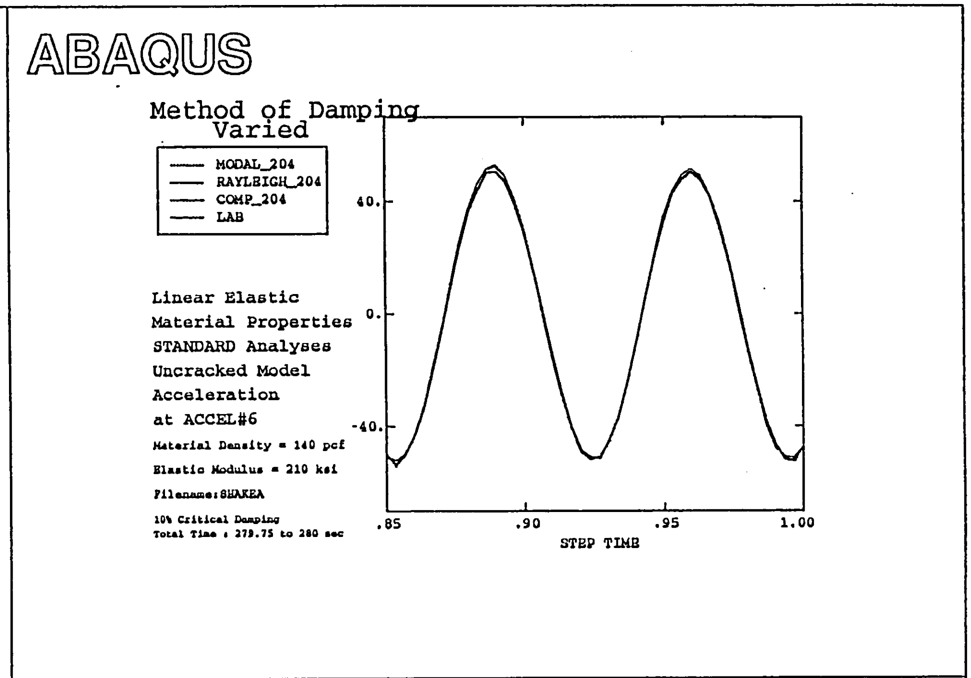
Elastic Modulus = 210 ksi; Material Density = 138.2 pcf

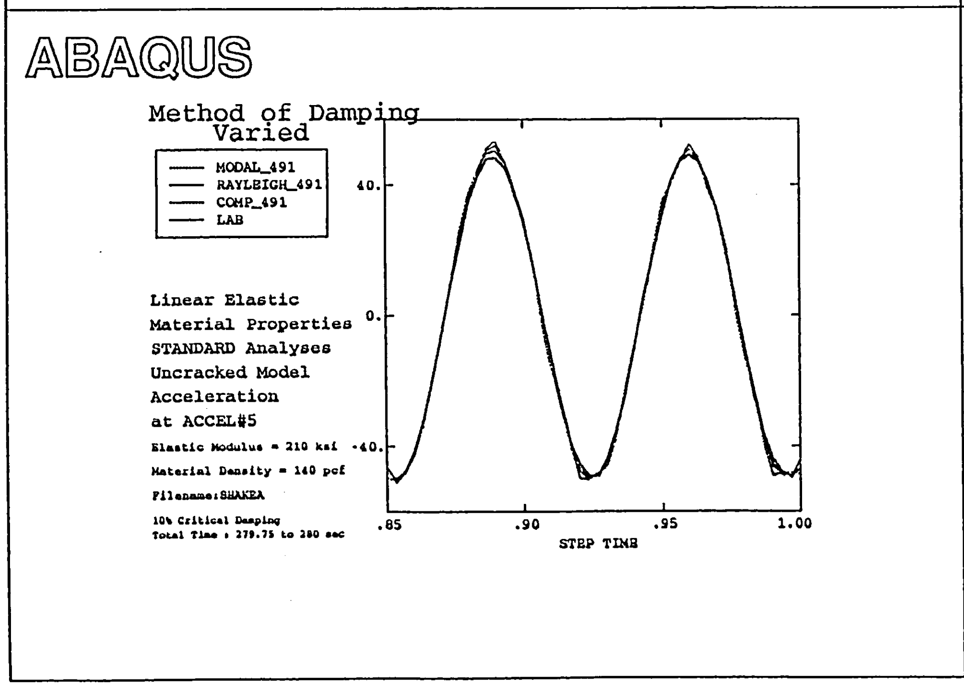


Peak Displacements (inches)				
	Modal	Rayleigh	Composite	
Method Number	1	2	3	LAB
LVDT#4	1.4E-03	1.4E-03	1.4E-03	7.8E-04
LVDT#3	5.2E-04	4.1E-04	5.2E-04	3.0E-04
LVDT#2	3.2E-04	2.2E-04	3.2E-04	1.8E-04
CPU TIME (SEC)	264	264	263	

Figure h19


ABAQUS
Method of Damping Varied
MODAL_176
RAYLEIGH_176
COMP_176
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Elastic Modulus = 210 ksi
Material Density = 140 pcf
Filename:SHAKEA
10% Critical Damping
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.85
.90
.95
1.00
STEP TIME


ABAQUS
Method of Damping Varied
MODAL_204
RAYLEIGH_204
COMP_204
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
10% Critical Damping
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME


ABAQUS
Method of Damping Varied
MODAL_491
RAYLEIGH_491
COMP_491
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Elastic Modulus = 210 ksi
Material Density = 140 pcf
Filename:SHAKEA
10% Critical Damping
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME

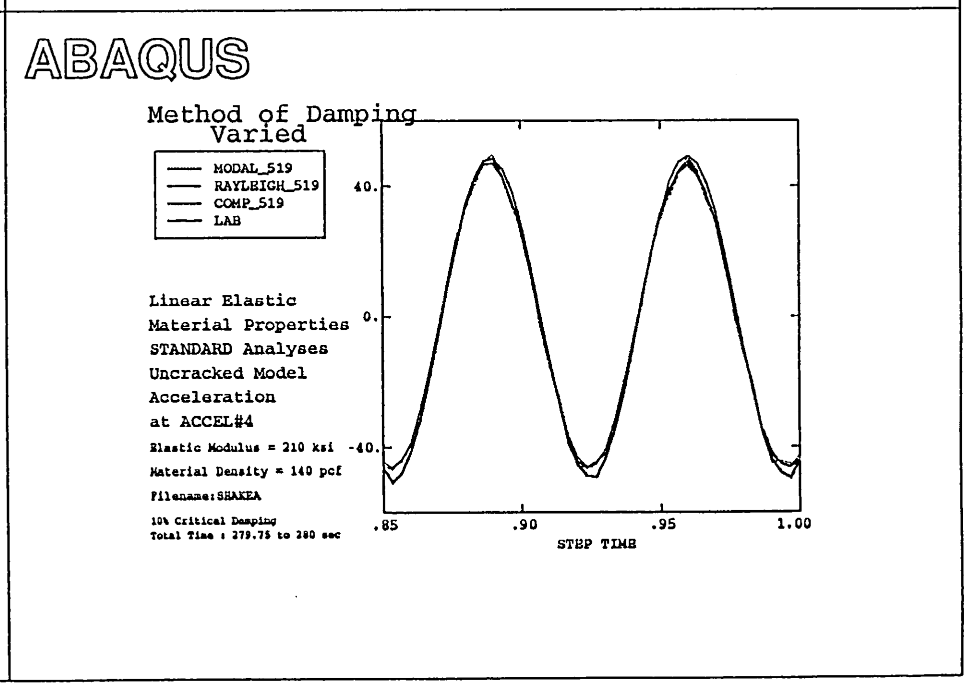
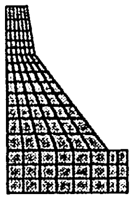

ABAQUS
Method of Damping Varied
MODAL_519
RAYLEIGH_519
COMP_519
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Elastic Modulus = 210 ksi
Material Density = 140 pcf
Filename:SHAKEA
10% Critical Damping
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME

Figure h20

ABAQUS

Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Damping Method

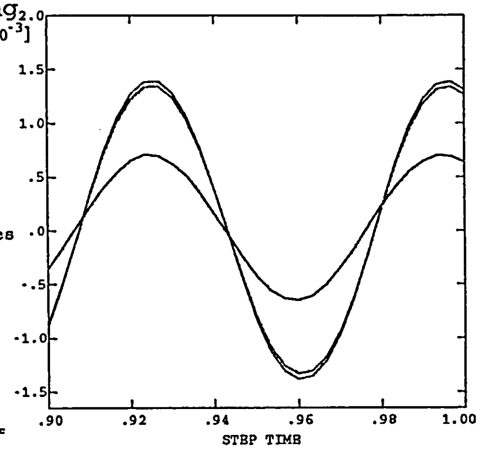
Comparison of Displacements
ABAQUS STANDARD
Modal Dynamic Analysis



Input Record SHAKEA
Elastic Modulus = 210 ksi
Density = 140.0 pcf
Mesh # 3
10 Percent Critical Damping

ABAQUS

Modal Damping

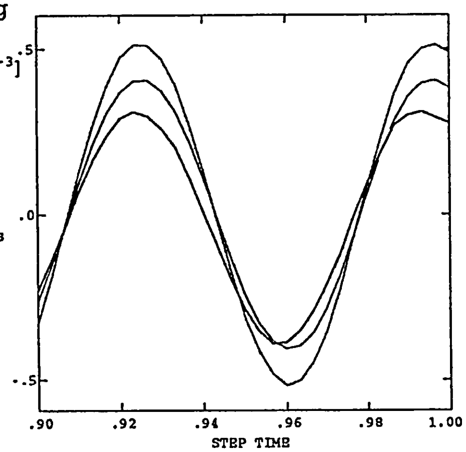


Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Displacement
at LVDT#4

Total Time : 279.90 to 280 sec

ABAQUS

Modal Damping

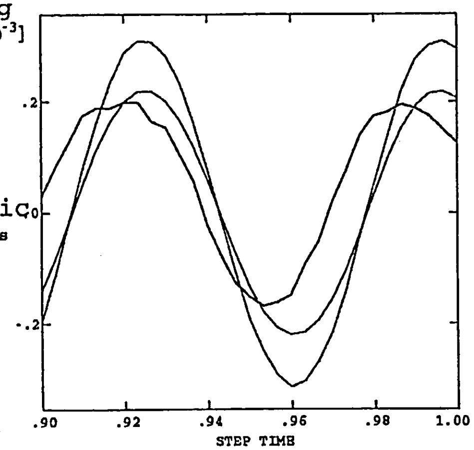


Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Displacement
at LVDT#3

Total Time : 279.90 to 280 sec

ABAQUS

Modal Damping



Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at LVDT#2

Total Time : 279.90 to 280 sec

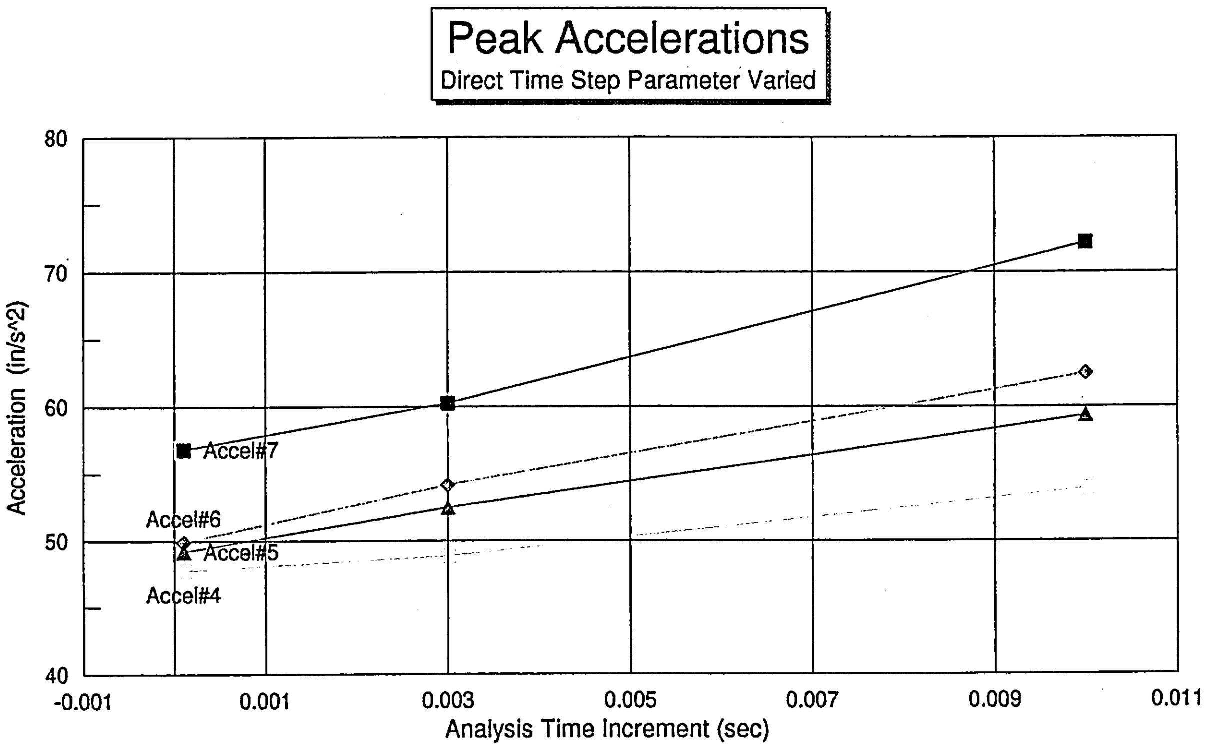
Figure h21

Appendix I
Sensitivity to Variation of Analysis Time Increment

Uncracked Koyna Laboratory Study

Direct Integration Dynamic Analysis
Sensitivity to Variation in Direct Time Step Parameter
Mesh#3

Elastic Modulus = 210 ksi;   Material Density = 140 pcf



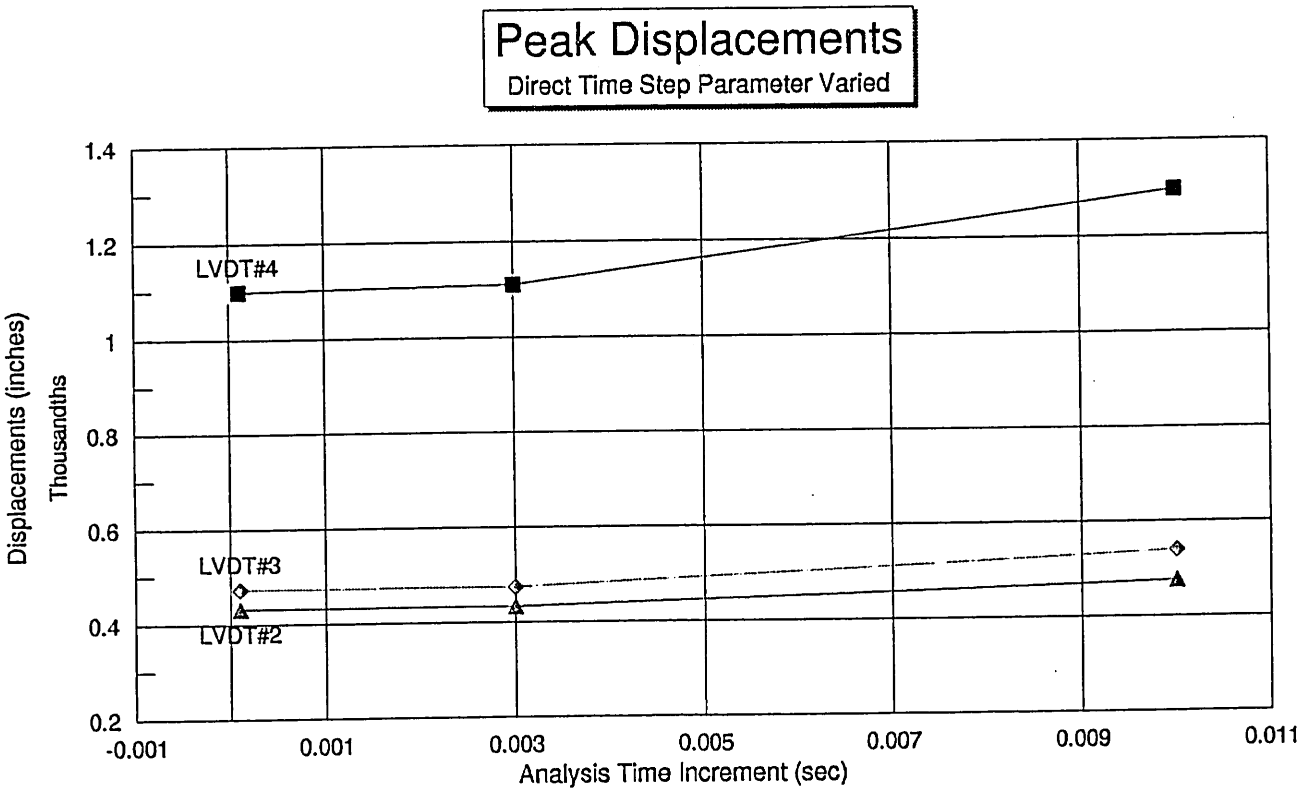
Peak Accelerations (inch / sec ^ 2)				
Direct Time Step	0.0001	0.003	0.01	LAB
Accel#7	56.81	60.26	72.18	53.26
Accel#6	49.87	54.17	62.47	51.72
Accel#5	49.19	52.47	59.36	49.26
Accel#4	47.75	48.86	53.94	47.72
CPU Time (sec)	39564	1441	557	

Figure i1

Uncracked Koyna Laboratory Study

Direct Integration Dynamic Analysis
Sensitivity to Variation in Direct Time Increment Parameter
Mesh#3

Elastic Modulus = 210 ksi; Material Density = 140 pcf



Peak Displacements (inches)				
Haftol Parameter	0.0001	0.003	0.01	LAB
LVDT#4	1.1E-03	1.1E-03	1.3E-03	7.8E-04
LVDT#3	4.7E-04	4.7E-04	5.4E-04	3.0E-04
LVDT#2	4.3E-04	4.3E-04	4.7E-04	1.8E-04
CPU Time (sec)	39564	1441	557	

Figure i2

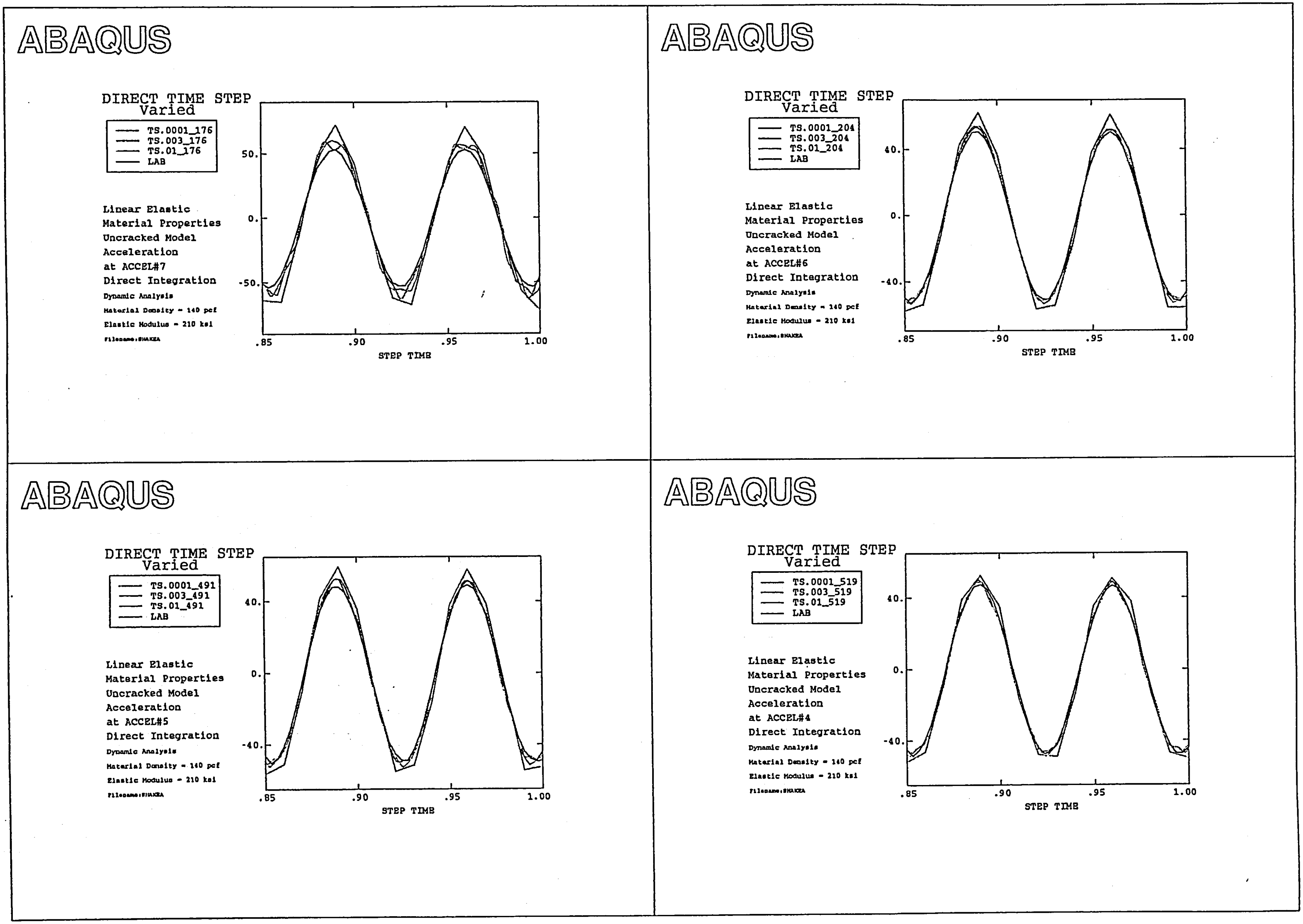

ABAQUS
DIRECT TIME STEP
Varied
TS.0001_176
TS.003_176
TS.01_176
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#7
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
50.
0.
-50.
.85
.90
.95
1.00
STEP TIME
ABAQUS
DIRECT TIME STEP
Varied
TS.0001_204
TS.003_204
TS.01_204
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#6
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS
DIRECT TIME STEP
Varied
TS.0001_491
TS.003_491
TS.01_491
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#5
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS
DIRECT TIME STEP
Varied
TS.0001_519
TS.003_519
TS.01_519
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#4
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME

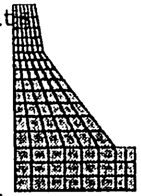
Figure 13

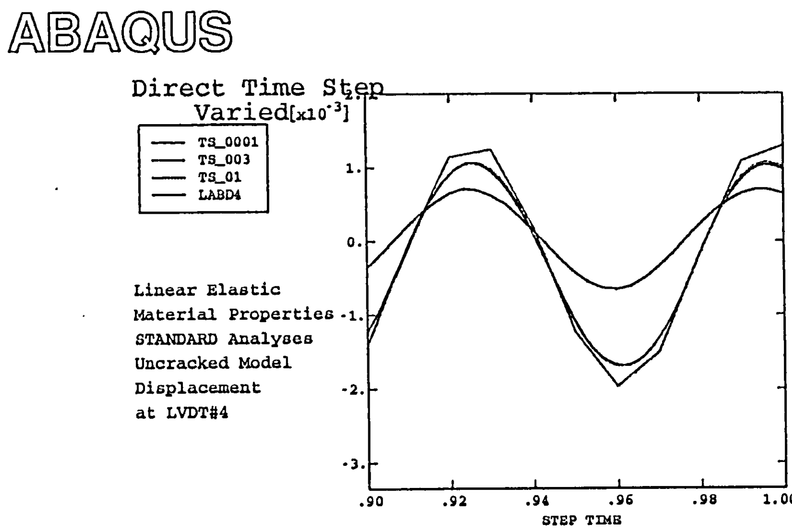
ABAQUS

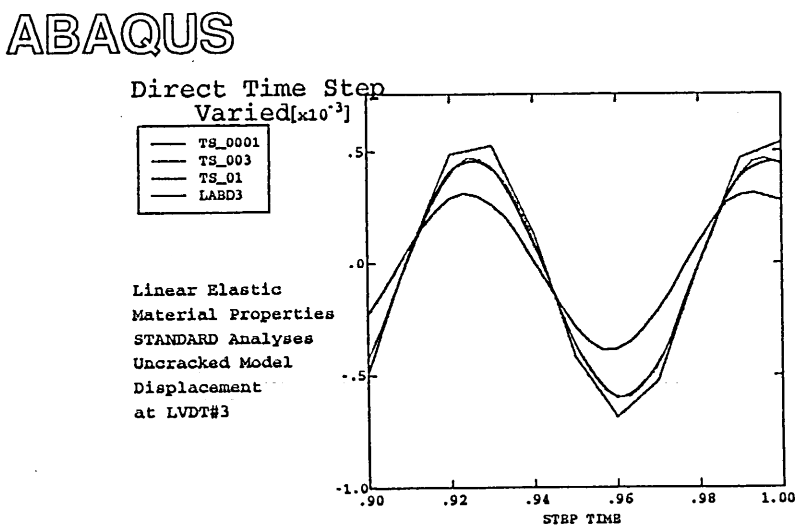
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Direct Time Step

Comparison of Displacements
Direct Integration
Dynamic Analysis

Input Record SHAKEA
Mesh # 3
Density = 140 pcf
Elastic Modulus = 210 ksi
Time Step = .0001, .003, & .01 sec







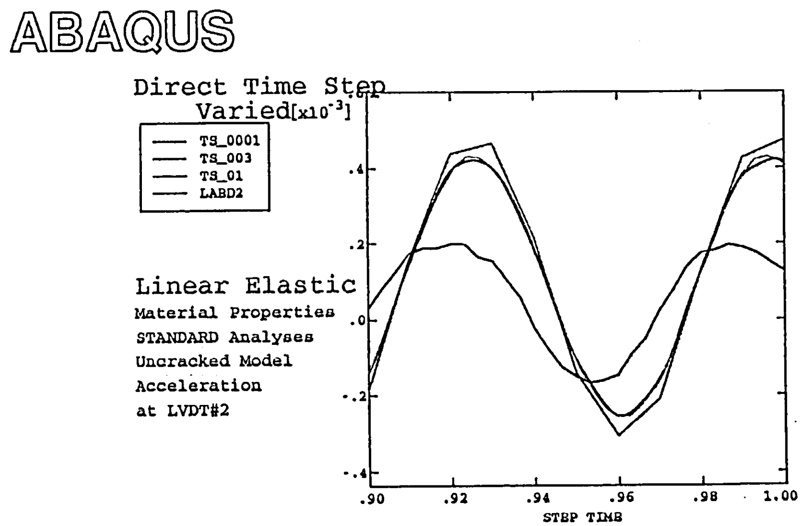
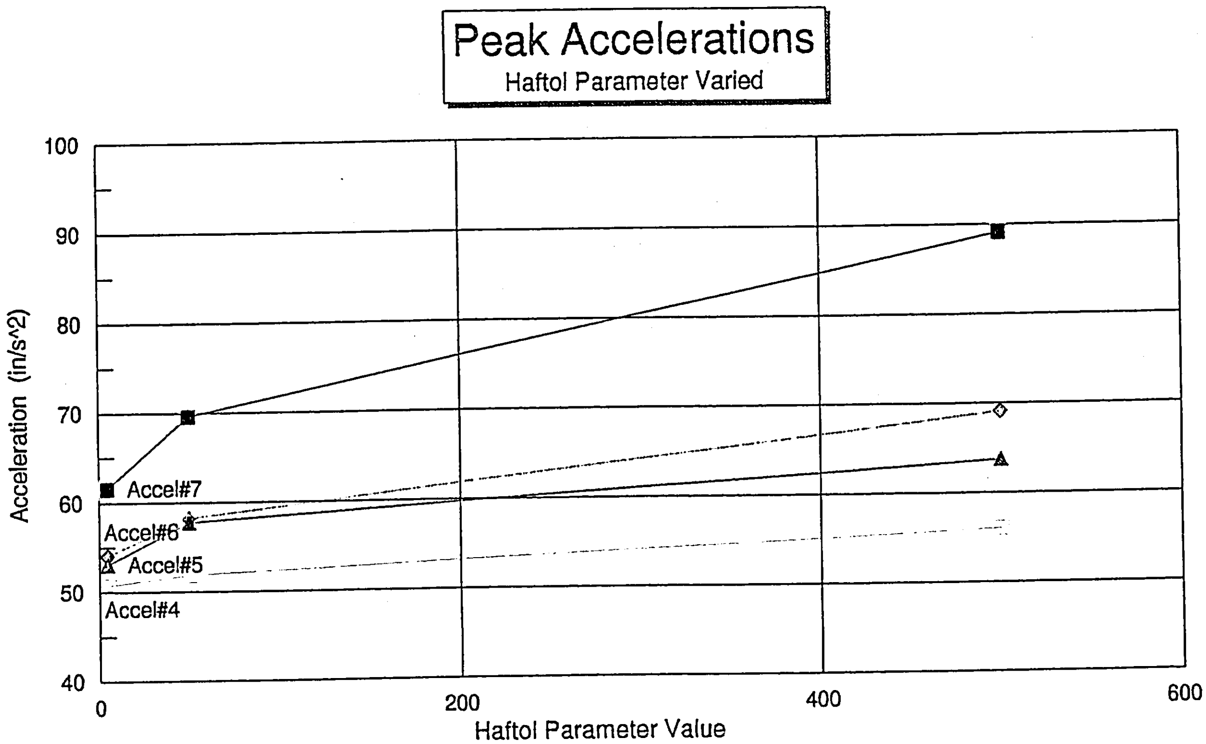


Figure 14

Uncracked Koyna Laboratory Study

Direct Integration Dynamic Analysis
Sensitivity to Variation in Haftol Parameter
Mesh#3

Elastic Modulus = 210 ksi;   Material Density = 140 pcf



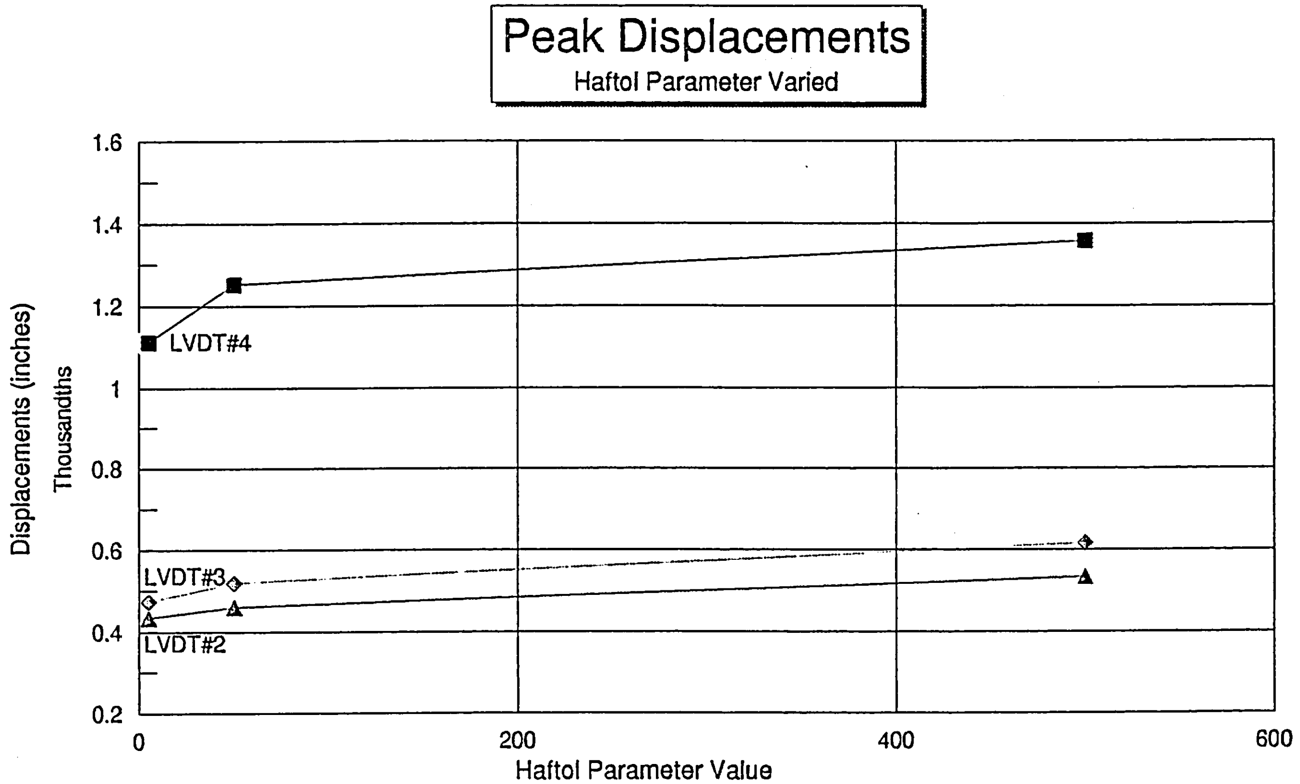
Peak Accelerations (inch / sec ^ 2)				
Haftol Parameter	5	50	500	LAB
Accel#7	61.51	69.62	89.07	53.26
Accel#6	54.09	58.23	69.14	51.72
Accel#5	53.04	57.73	63.71	49.26
Accel#4	50.75	51.88	56.01	47.72
CPU Time (sec)	3179	1230	785	

Figure i5

Uncracked Koyna Laboratory Study

Direct Integration Dynamic Analysis
Sensitivity to Variation in Haftol Parameter
Mesh#3

Elastic Modulus = 210 ksi; Material Density = 140 pcf



Peak Displacements (inches)				
Haftol Parameter	5	50	500	LAB
LVDT#4	1.1E-03	1.3E-03	1.4E-03	7.8E-04
LVDT#3	4.7E-04	5.2E-04	6.2E-04	3.0E-04
LVDT#2	4.3E-04	4.6E-04	5.3E-04	1.8E-04
CPU Time (sec)	3179	1230	785	

Figure i6

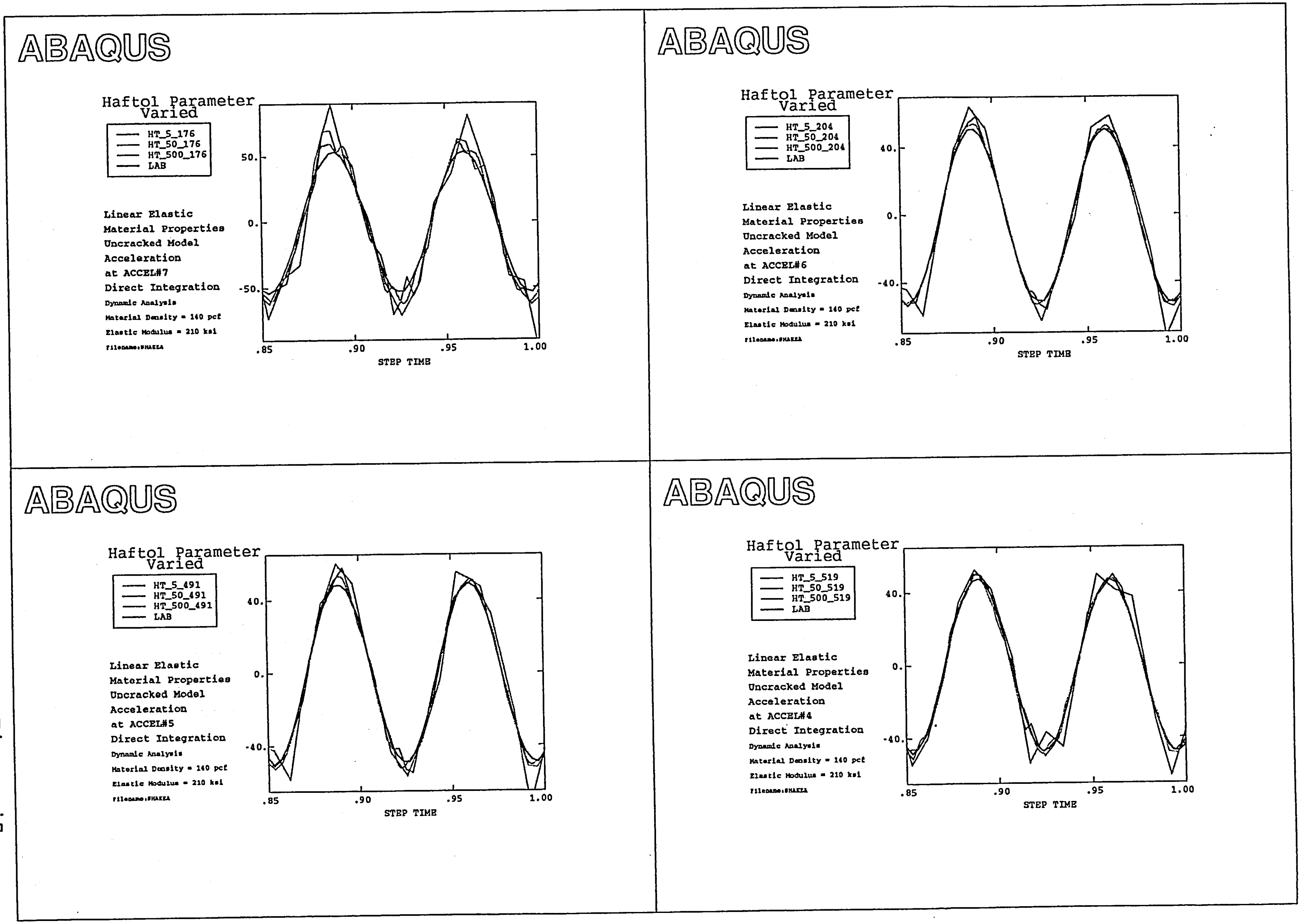

ABAQUS
Haftol Parameter Varied
HT_5_176
HT_50_176
HT_500_176
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#7
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
50.
0.
-50.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Haftol Parameter Varied
HT_5_204
HT_50_204
HT_500_204
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#6
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Haftol Parameter Varied
HT_5_491
HT_50_491
HT_500_491
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#5
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Haftol Parameter Varied
HT_5_519
HT_50_519
HT_500_519
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#4
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME

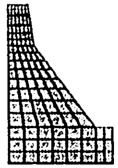
Figure 17

ABAQUS

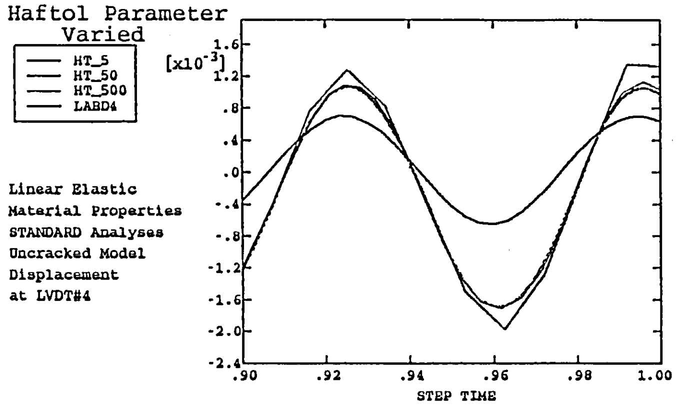
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Haftol Parameter

Comparison of Displacements
Direct Integration
Dynamic Analysis

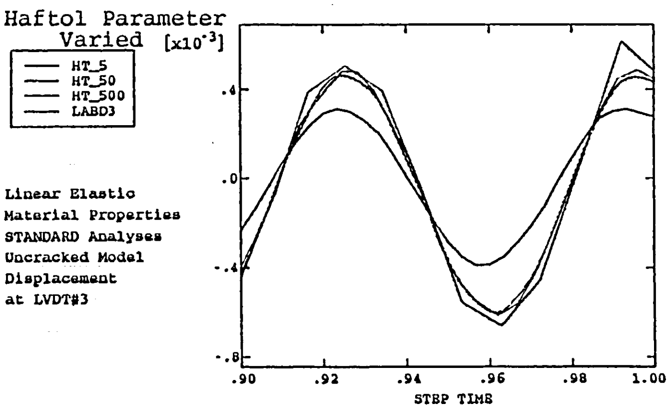
Input Record SHAKEA
Haftol = 5, 50, & 500
Density = 140 pcf
Elastic Modulus = 210 ksi
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

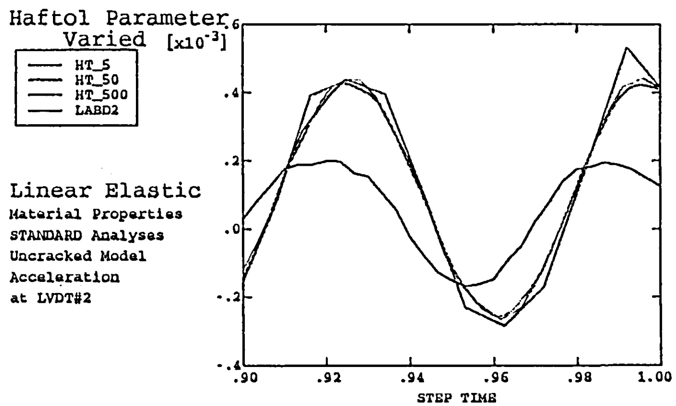
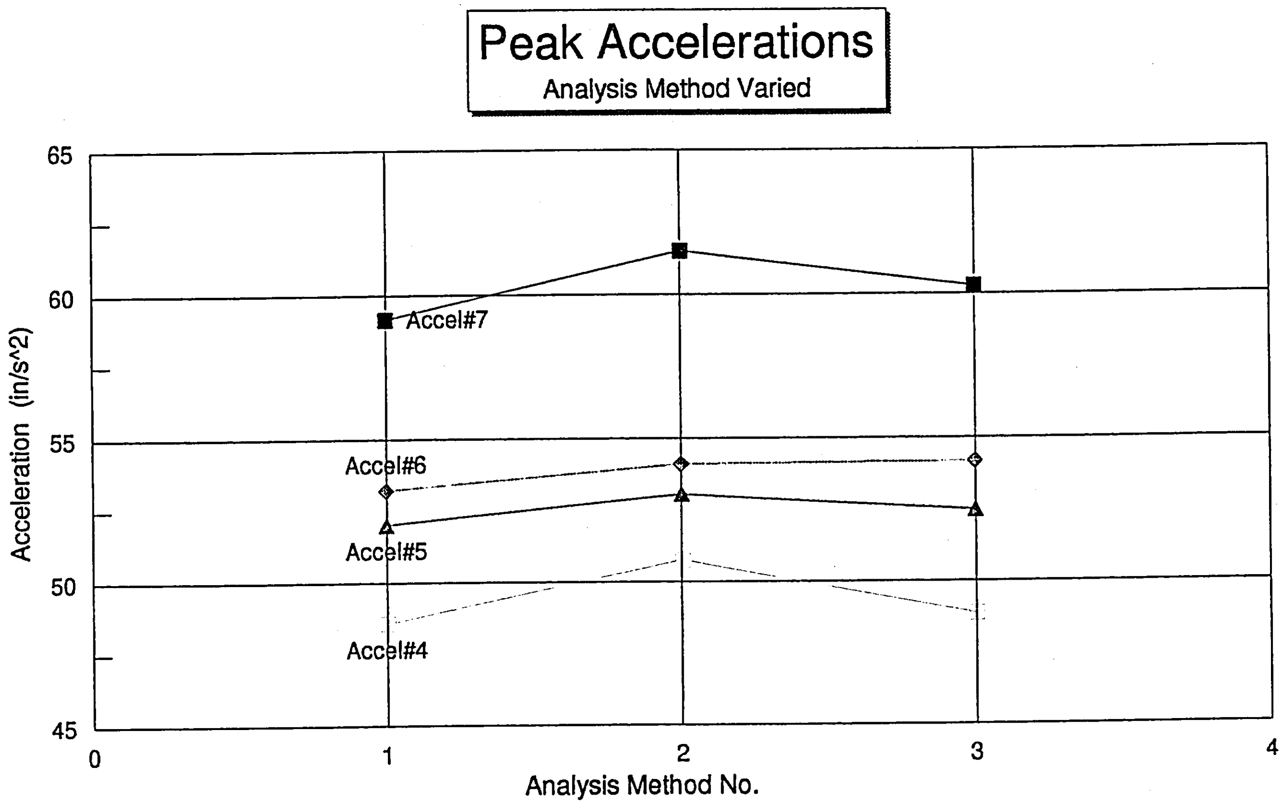


Figure 18

Appendix J
Comparison of
Analysis Procedures

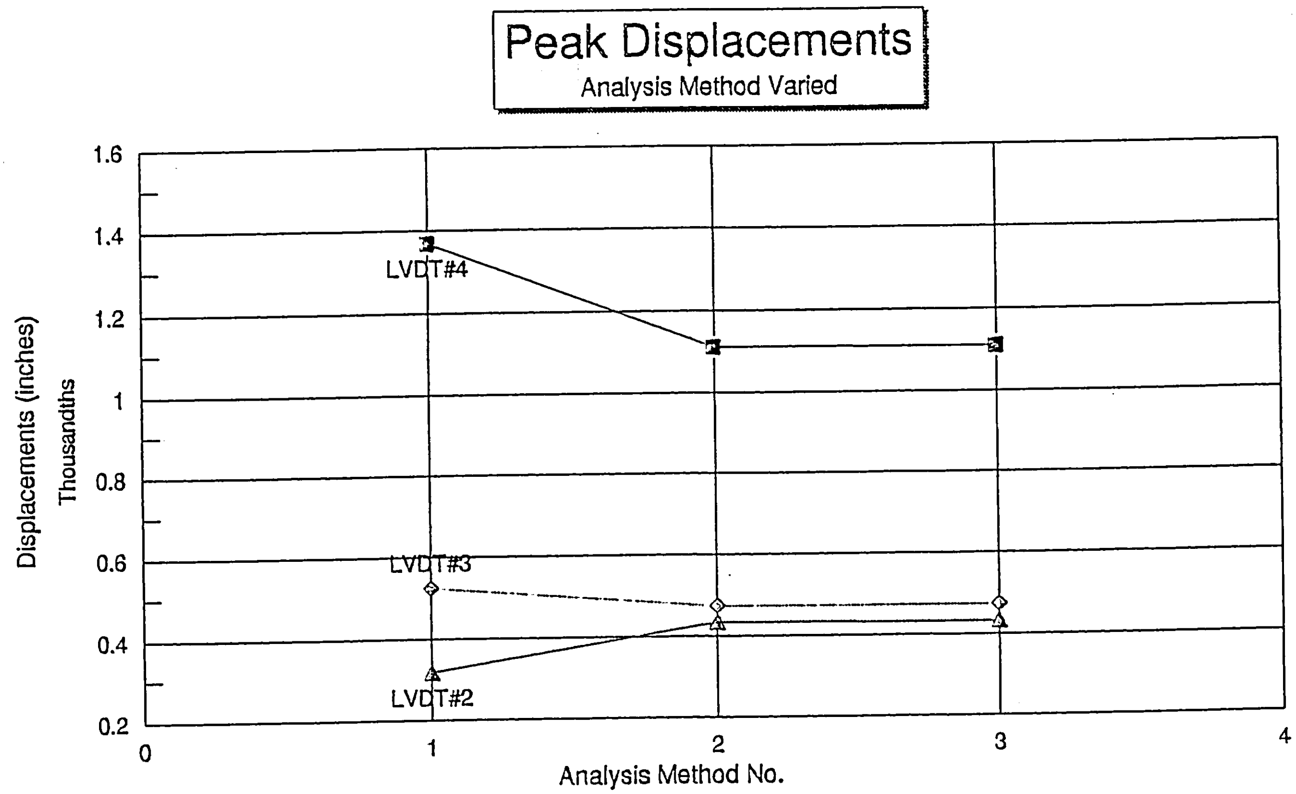
Uncracked Koyna Laboratory Study
Sensitivity to Variation Analysis Method
Mesh#3
Modal Analysis Methods
Direct Integration using Haftol Parameter = 5
Direct Integration using Direct time Step = .003 sec
Modal Analysis
10 Percent of Critical Damping
Elastic Modulus = 210 ksi;   Material Density = 139 pcf



Peak Accelerations (inch / sec ^ 2)				
	Modal	Direct Haftol=5	Direct Time Step=.003	
Method Number	1	2	3	LAB
Accel#7	59.15	61.51	60.26	53.26
Accel#6	53.21	54.09	54.17	51.72
Accel#5	52.02	53.04	52.47	49.26
Accel#4	48.57	50.75	48.86	47.72
CPU TIME (SEC)	264	3179	1441	

Figure j1

Uncracked Koyna Laboratory Study
Sensitivity to Variation Analysis Method
Mesh#3
Modal Analysis Methods
Direct Integration using Haftol Parameter = 5
Direct Integration using Direct time Step = .003 sec
Modal Analysis
10 Percent of Critical Damping
Elastic Modulus = 210 ksi; Material Density = 139 pcf



Peak Displacements (inches)				
	Modal	Direct Haftol=5	Direct Time Step=.003	
Method Number	1	2	3	LAB
LVDT#4	1.4E-03	1.1E-03	1.1E-03	7.8E-04
LVDT#3	5.2E-04	4.7E-04	4.7E-04	3.0E-04
LVDT#2	3.2E-04	4.3E-04	4.3E-04	1.8E-04
CPU TIME (SEC)	264	3179	1441	

Figure j2

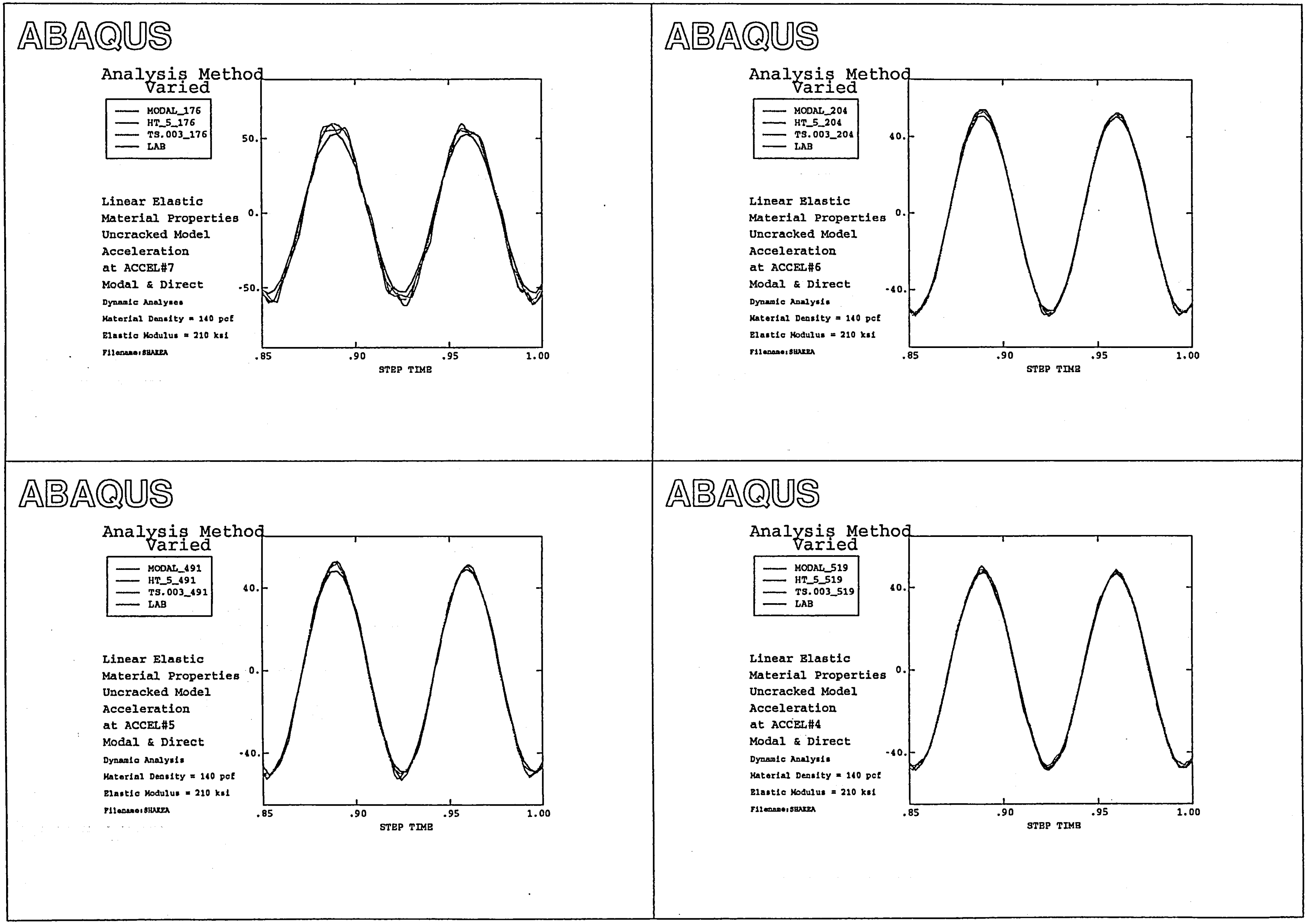

ABAQUS
Analysis Method Varied
MODAL_176
HT_5_176
TS.003_176
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#7
Modal & Direct
Dynamic Analyses
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
50.
0.
-50.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Analysis Method Varied
MODAL_204
HT_5_204
TS.003_204
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#6
Modal & Direct
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Analysis Method Varied
MODAL_491
HT_5_491
TS.003_491
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#5
Modal & Direct
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Analysis Method Varied
MODAL_519
HT_5_519
TS.003_519
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#4
Modal & Direct
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME

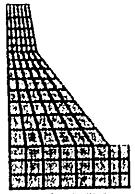
Figure J3

ABAQUS

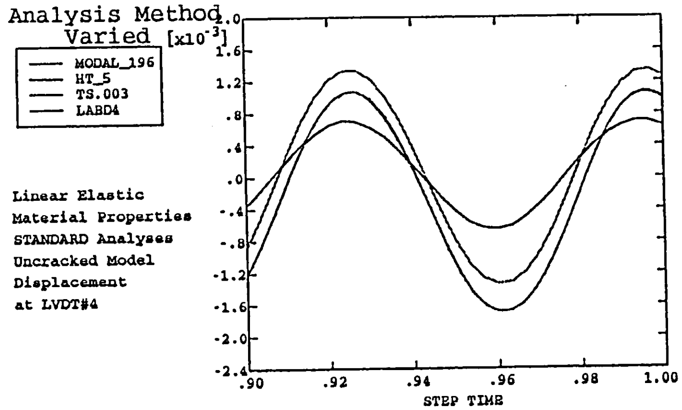
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Analysis Method

Comparison of Displacements
Modal & Direct Integration
Dynamic Analysis

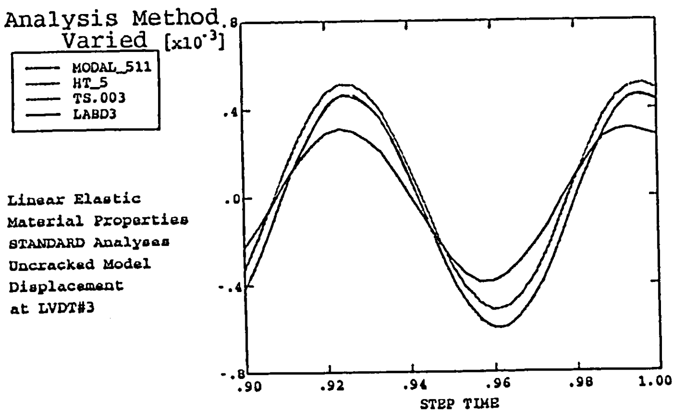
Input Record SHAKEA
Mesh # 3
Density = 140 pcf
Elastic Modulus = 210 ksi



ABAQUS



ABAQUS



ABAQUS

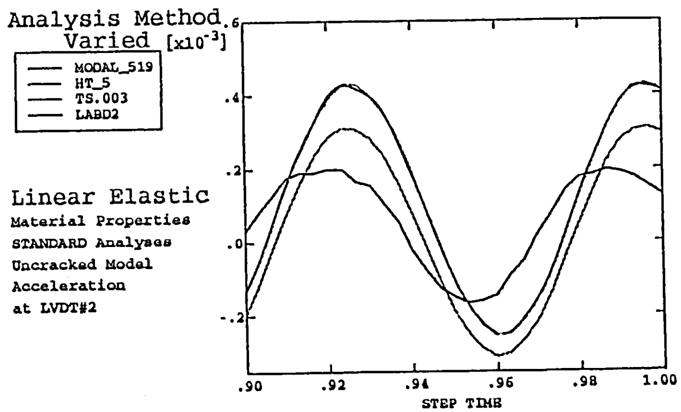


Figure J4

Appendix K
Nonlinear Analysis

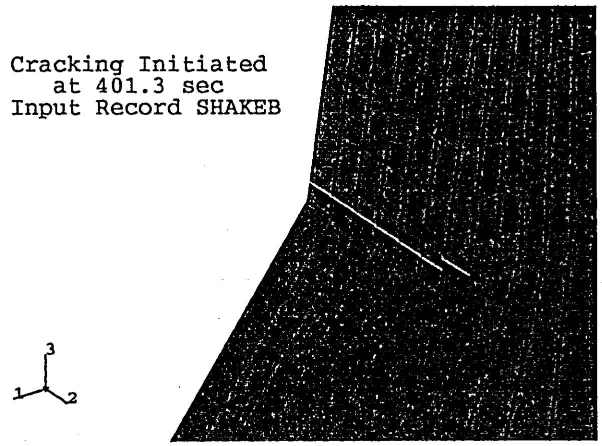
ABAQUS

Koyna Laboratory Model Study
Uncracked Model Study

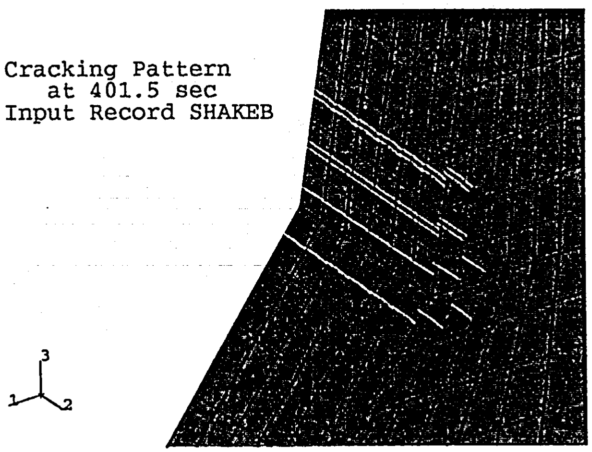
Determination of Mesh Sensitivity
Non-linear Material Propertys
Failure Stress = 55 psi
Mode I Fracture Energy = 0.2012
Crack Opening Strain = .001375

Explicit Analysis
with Mesh #3

ABAQUS



ABAQUS



ABAQUS

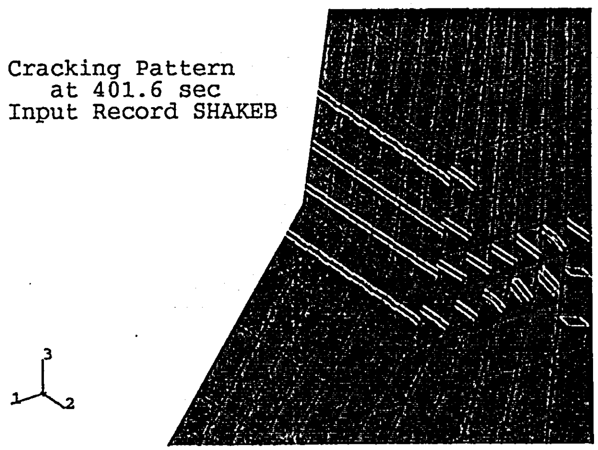


Figure k1

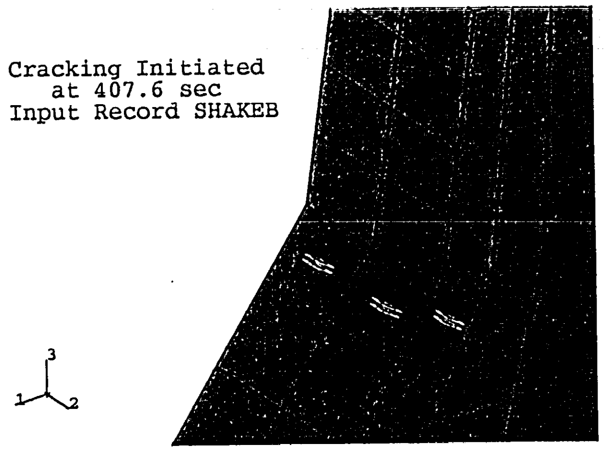
ABAQUS

Koyna Laboratory Model Study
Uncracked Model Study

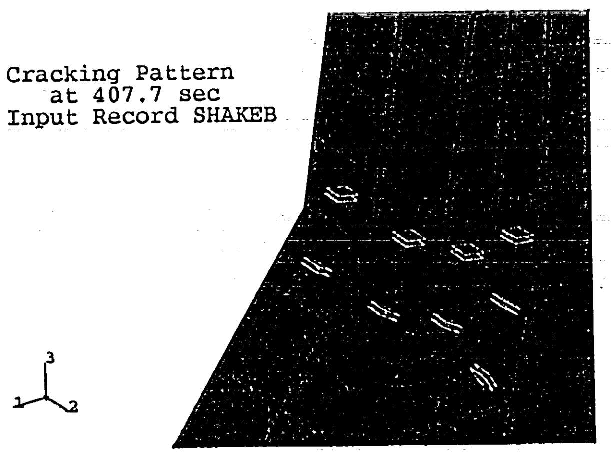
Determination of Mesh Sensitivity
Non-linear Material Propertys
Failure Stress = 55 psi
Mode I Fracture Energy = 0.2012
Crack Opening Strain = .001375

Explicit Analysis
with Mesh #5

ABAQUS



ABAQUS



ABAQUS

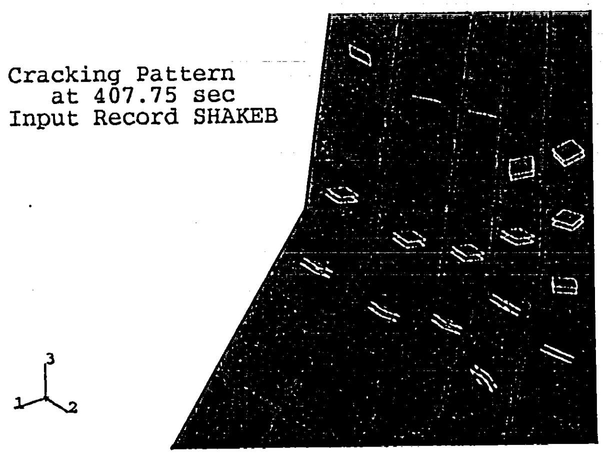


Figure k2

ABAQUS

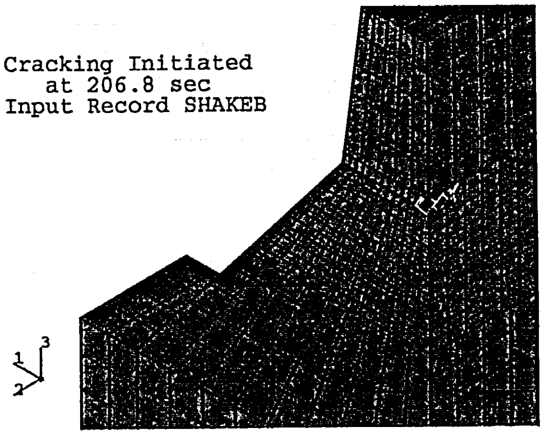
Koyna Laboratory Model Study
Uncracked Model Study

Determination of Mesh Sensitivity
Non-linear Material Propertys
Failure Stress = 55 psi
Mode I Fracture Energy = 0.2012
Crack Opening Strain = .001375

Explicit Analysis
with Mesh #1

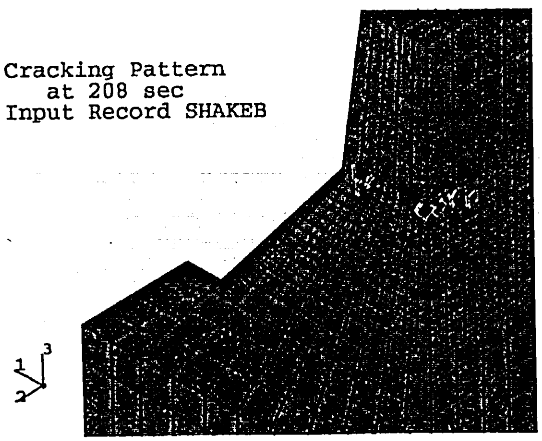
ABAQUS

Cracking Initiated
at 206.8 sec
Input Record SHAKEB



ABAQUS

Cracking Pattern
at 208 sec
Input Record SHAKEB



ABAQUS

Cracking Pattern
at 210.5 sec
Input Record SHAKEB

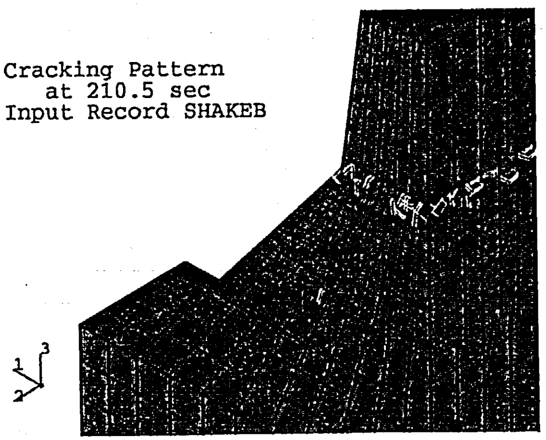


Figure k3

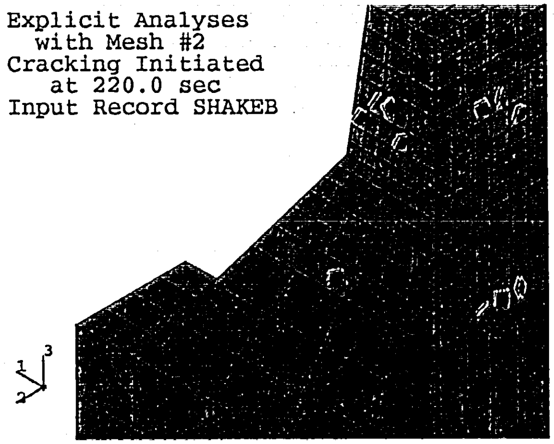
ABAQUS

Koyna Laboratory Model Study
Uncracked Model Study

Determination of Mesh Sensitivity
Non-linear Material Propertys
Failure Stress = 55 psi
Mode I Fracture Energy = 0.2012
Crack Opening Strain = .001375

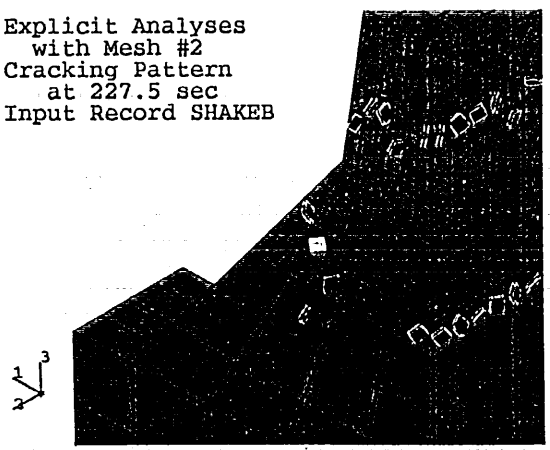
ABAQUS

Explicit Analyses
with Mesh #2
Cracking Initiated
at 220.0 sec
Input Record SHAKEB



ABAQUS

Explicit Analyses
with Mesh #2
Cracking Pattern
at 227.5 sec
Input Record SHAKEB



ABAQUS

Explicit Analyses
with Mesh #2
Cracking Failure
at 232.5 sec
Input Record SHAKEB

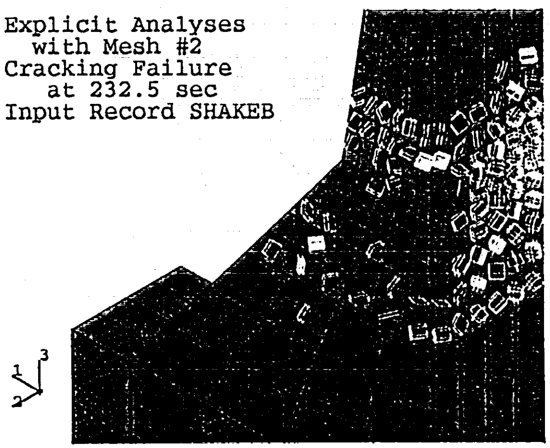


Figure k4

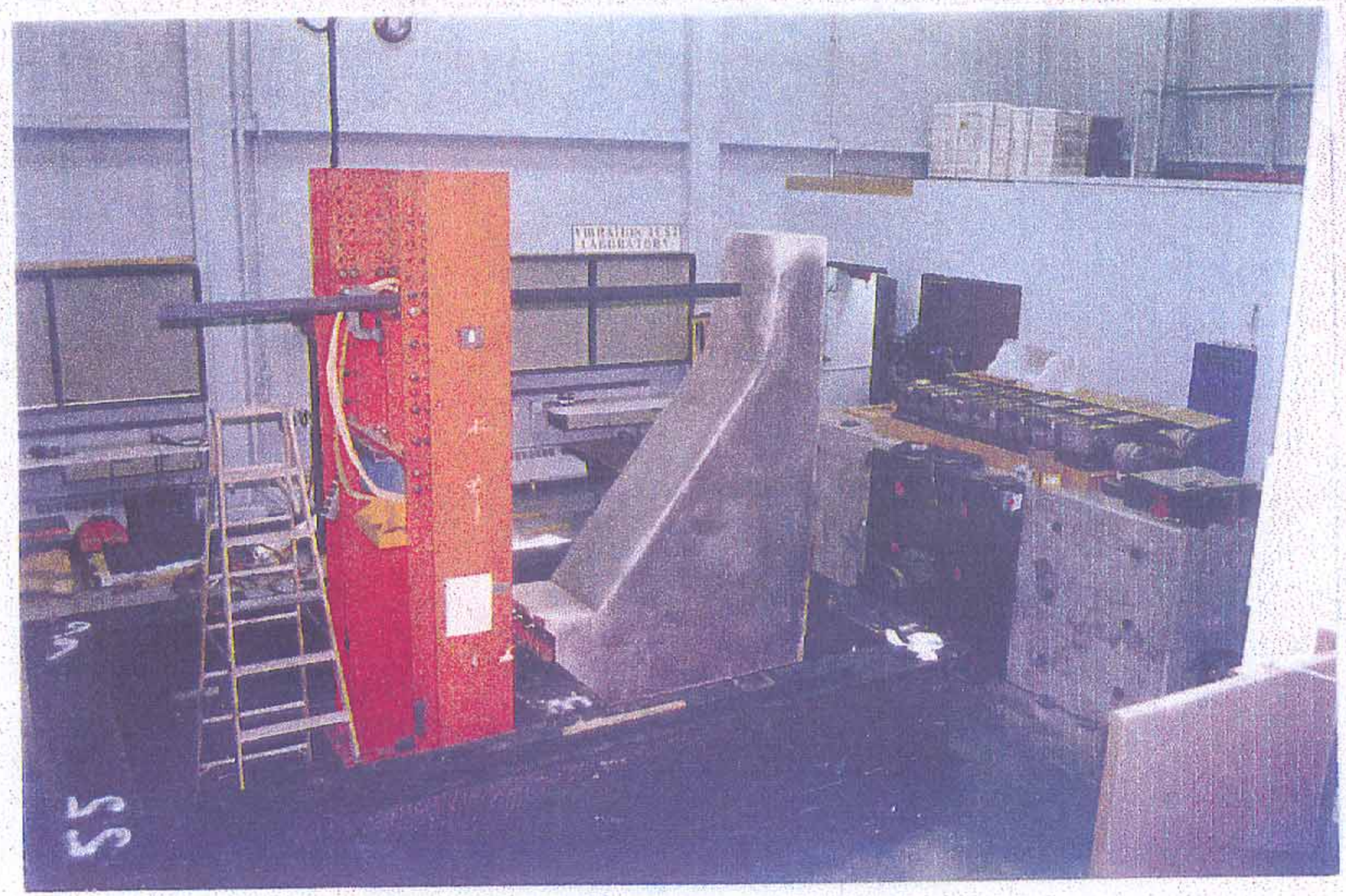
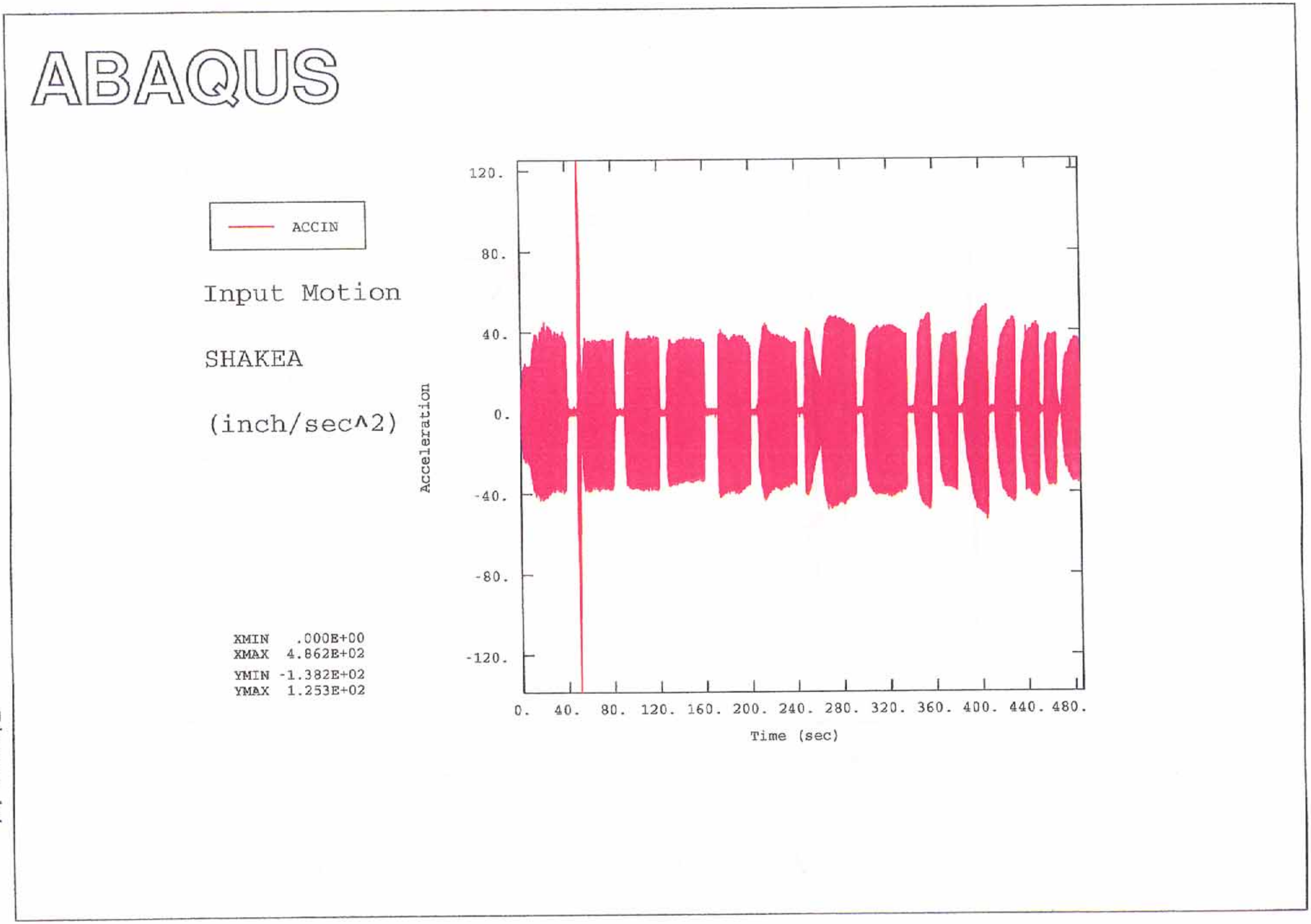
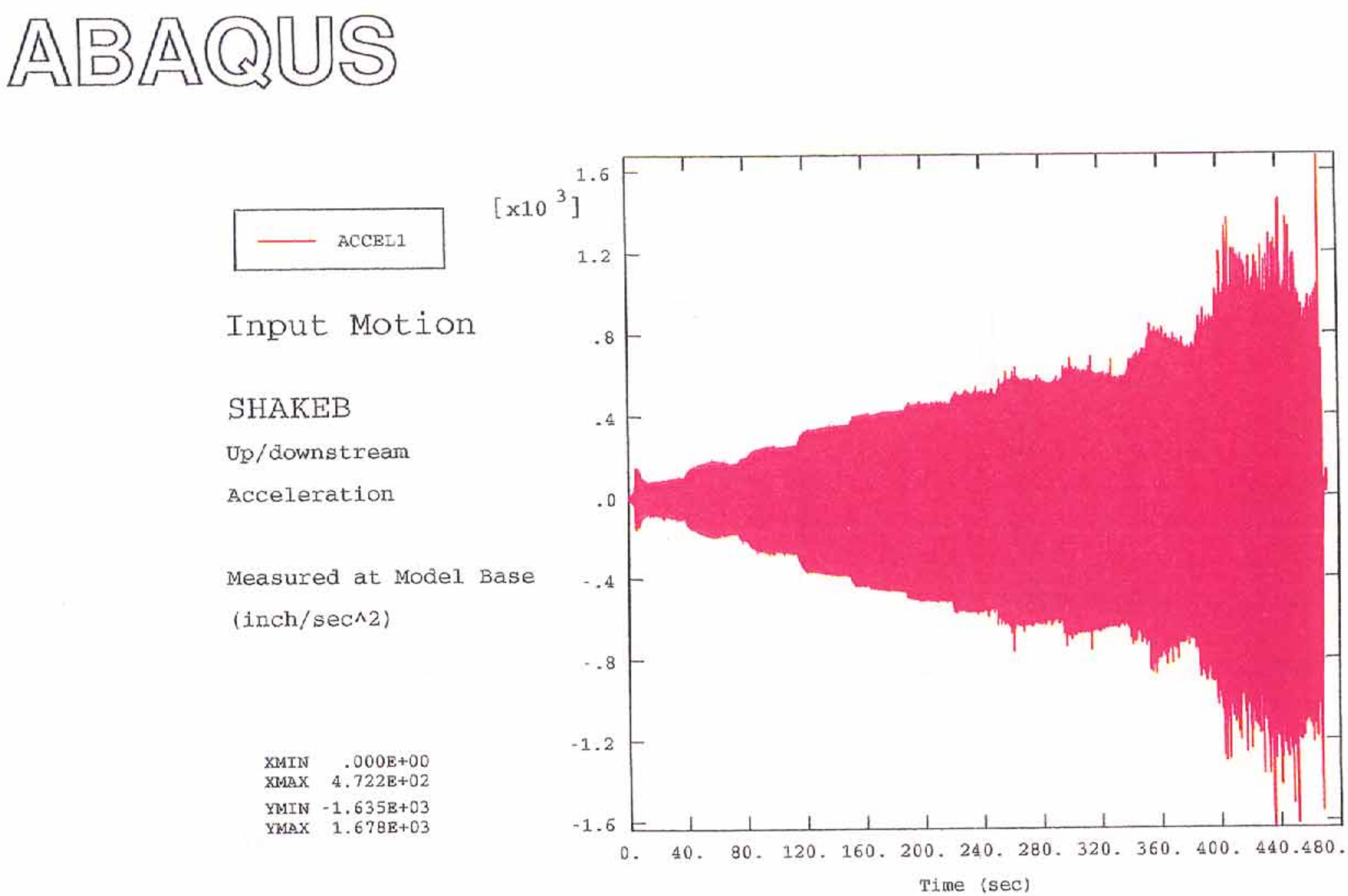


Figure b1



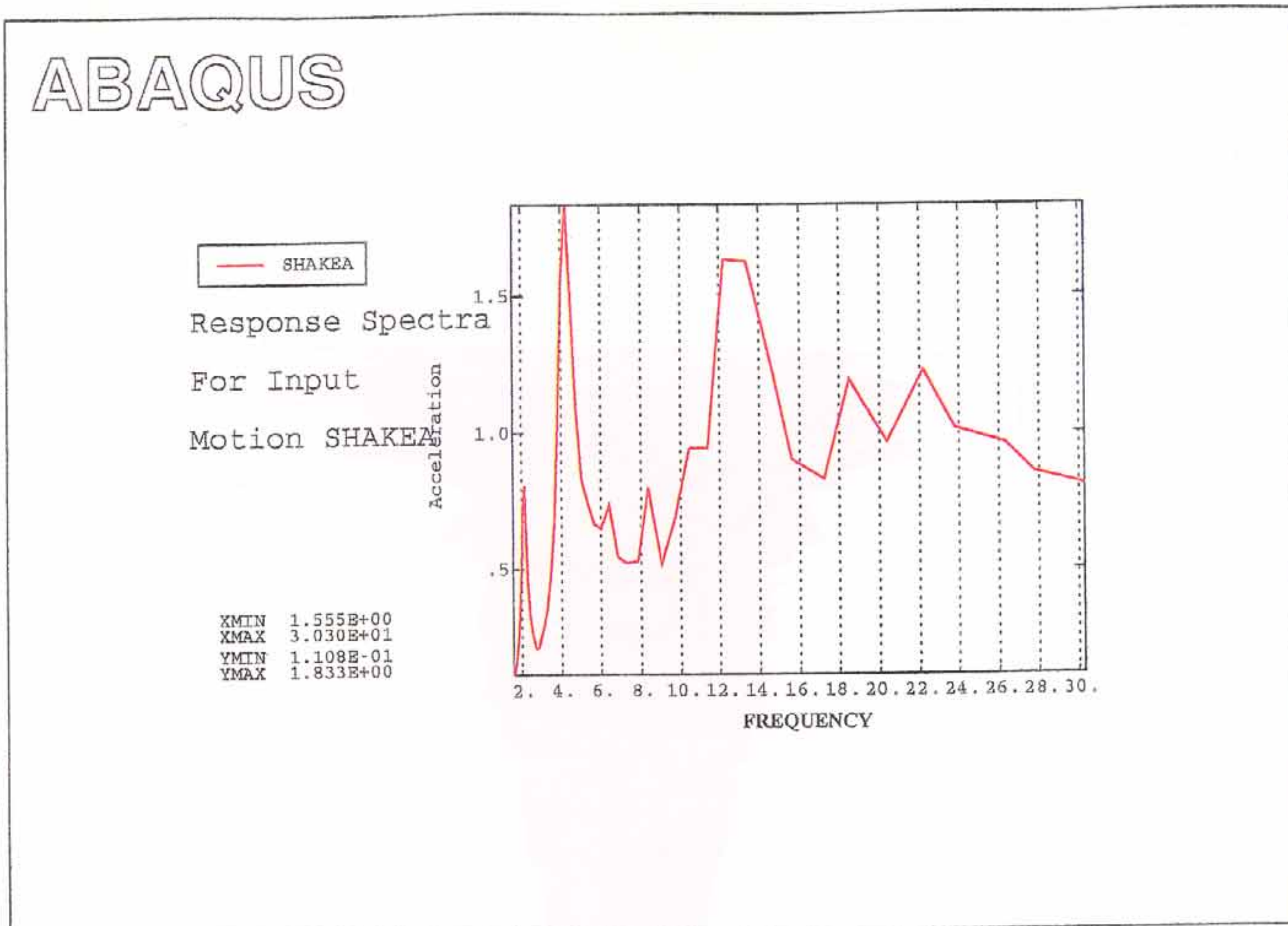
ABAQUS
ACCIN
Input Motion
SHAKEA
(inch/sec^2)
XMIN .000E+00
XMAX 4.862E+02
YMIN -1.382E+02
YMAX 1.253E+02
Acceleration
120.
80.
40.
0.
-40.
-80.
-120.
0. 40. 80. 120. 160. 200. 240. 280. 320. 360. 400. 440. 480.
Time (sec)

Figure b4



ABAQUS
ACCEL1
Input Motion
SHAKEB
Up/downstream
Acceleration
Measured at Model Base
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.635E+03
YMAX 1.678E+03
[x10 3]
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
0. 40. 80. 120. 160. 200. 240. 280. 320. 360. 400. 440. 480.
Time (sec)

Figure b5


ABAQUS
SHAKEA
Response Spectra
For Input
Motion SHAKEA
Acceleration
1.5
1.0
.5
XMIN 1.555E+00
XMAX 3.030E+01
YMIN 1.108E-01
YMAX 1.833E+00
2. 4. 6. 8. 10. 12. 14. 16. 18. 20. 22. 24. 26. 28. 30.
FREQUENCY

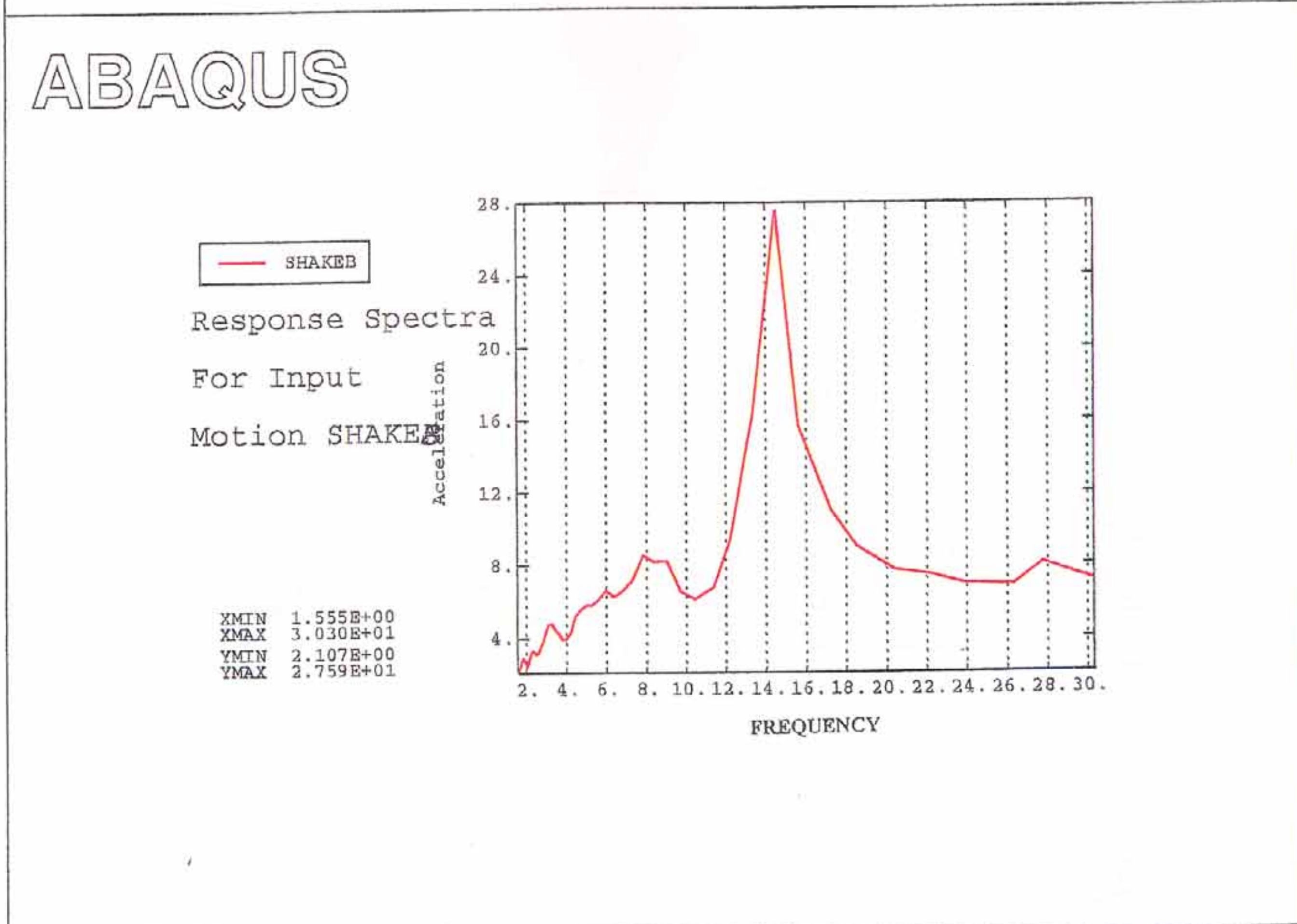

ABAQUS
SHAKEB
Response Spectra
For Input
Motion SHAKEB
Acceleration
28.
24.
20.
16.
12.
8.
4.
XMIN 1.555E+00
XMAX 3.030E+01
YMIN 2.107E+00
YMAX 2.759E+01
2. 4. 6. 8. 10. 12. 14. 16. 18. 20. 22. 24. 26. 28. 30.
FREQUENCY

Figure b6

ABAQUS

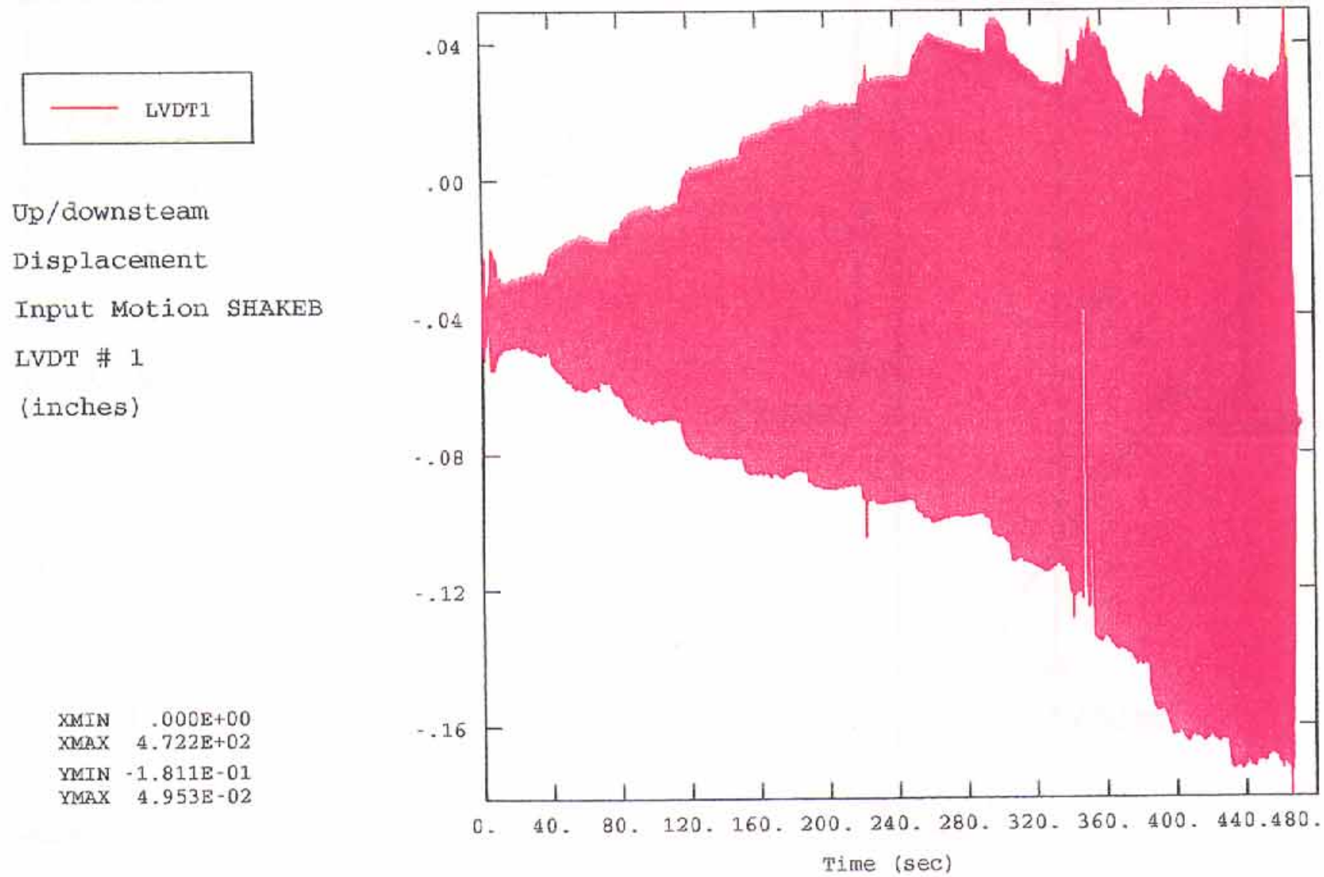


Figure b7

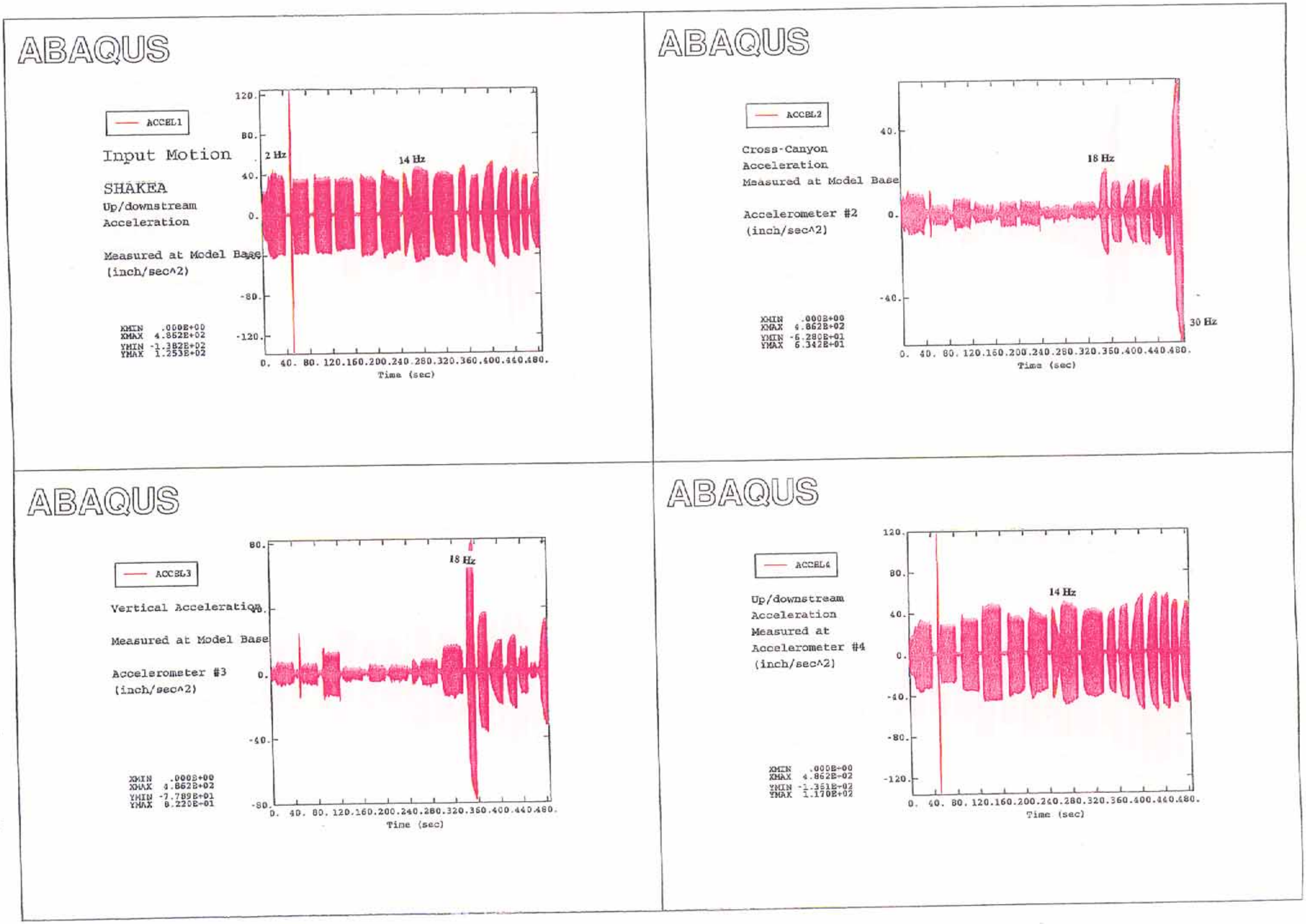

ABAQUS
ACCEL1
Input Motion
SHAKEA
Up/downstream
Acceleration
Measured at Model Base
(inch/sec^2)
2 Hz
14 Hz
Time (sec)
ABAQUS
ACCEL2
Cross-Canyon
Acceleration
Measured at Model Base
Accelerometer #2
(inch/sec^2)
18 Hz
30 Hz
Time (sec)
ABAQUS
ACCEL3
Vertical Acceleration
Measured at Model Base
Accelerometer #3
(inch/sec^2)
18 Hz
Time (sec)
ABAQUS
ACCEL4
Up/downstream
Acceleration
Measured at
Accelerometer #4
(inch/sec^2)
14 Hz
Time (sec)

Figure C1

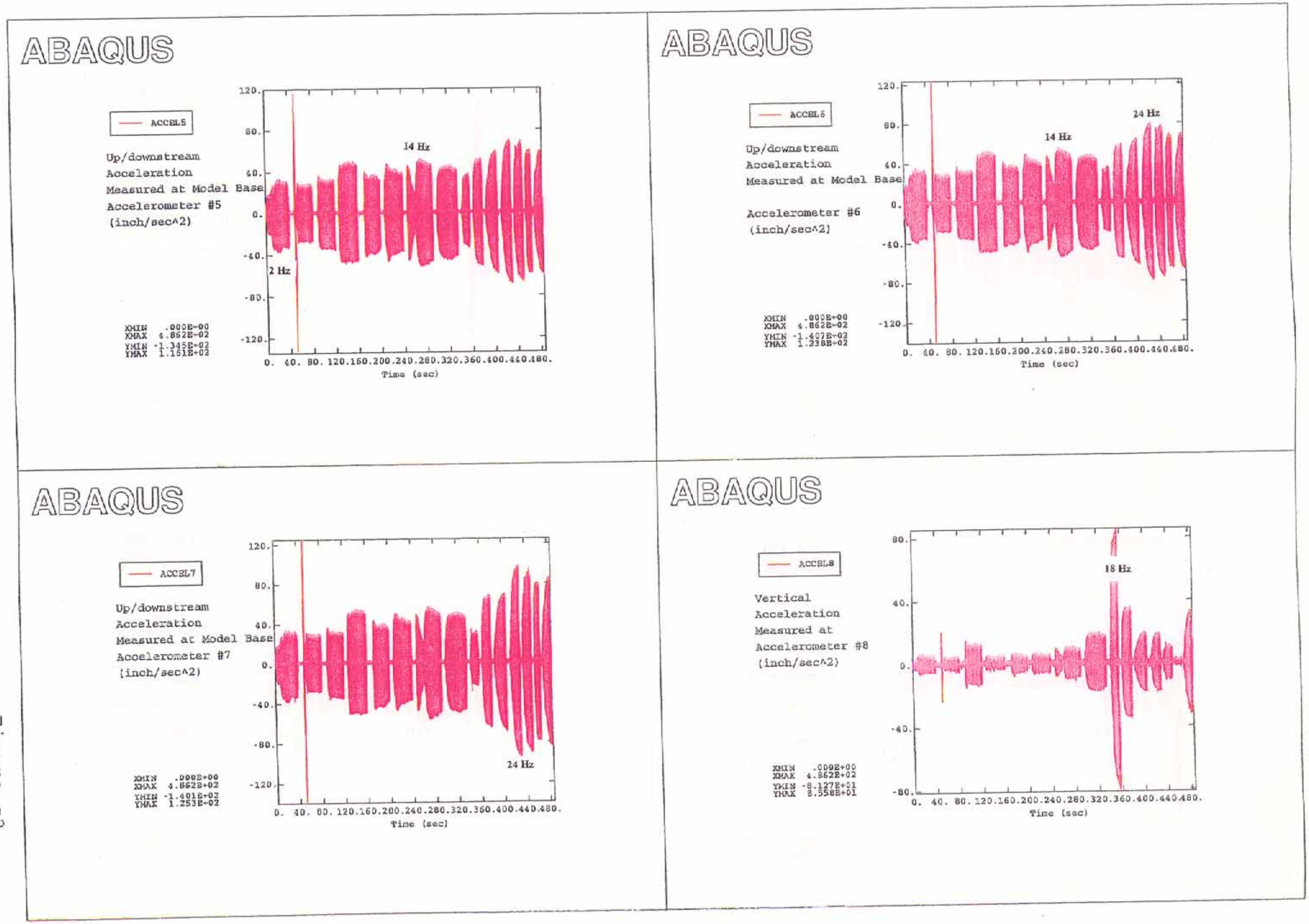
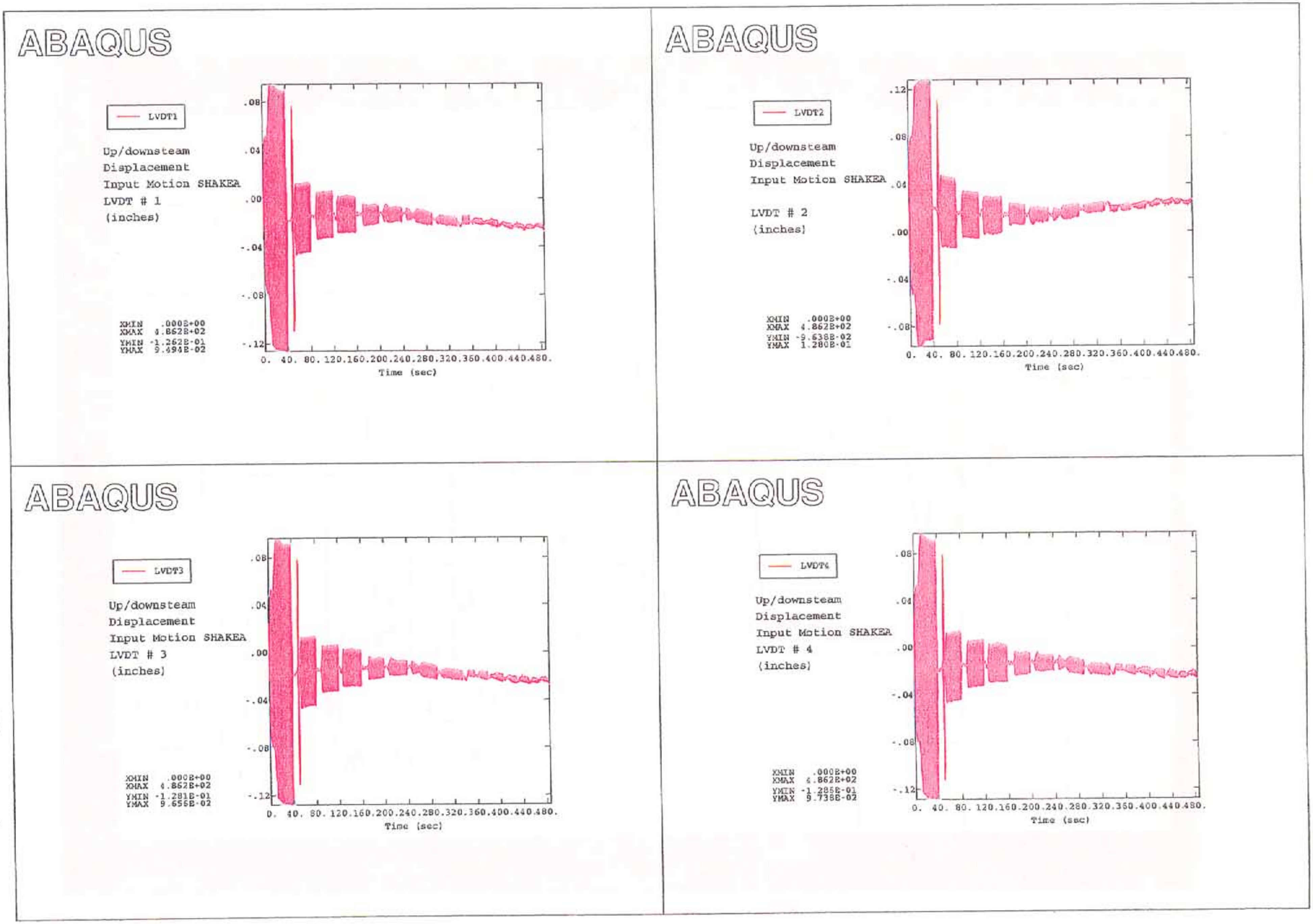

ABAQUS
ACCEL5
Up/downstream
Acceleration
Measured at Model Base
Accelerometer #5
(inch/sec^2)
14 Hz
2 Hz
Time (sec)
ABAQUS
ACCEL6
Up/downstream
Acceleration
Measured at Model Base
Accelerometer #6
(inch/sec^2)
14 Hz
24 Hz
Time (sec)
ABAQUS
ACCEL7
Up/downstream
Acceleration
Measured at Model Base
Accelerometer #7
(inch/sec^2)
24 Hz
Time (sec)
ABAQUS
ACCEL8
Vertical
Acceleration
Measured at
Accelerometer #8
(inch/sec^2)
18 Hz
Time (sec)

Figure C2



ABAQUS
LVDT1
Up/downsteam
Displacement
Input Motion SHAKEA
LVDT # 1
(inches)
XMIN .000E+00
XMAX 4.862E+02
YMIN -1.262E-01
YMAX 9.494E-02
Time (sec)
ABAQUS
LVDT2
Up/downsteam
Displacement
Input Motion SHAKEA
LVDT # 2
(inches)
XMIN .000E+00
XMAX 4.862E+02
YMIN -9.638E-02
YMAX 1.280E-01
Time (sec)
ABAQUS
LVDT3
Up/downsteam
Displacement
Input Motion SHAKEA
LVDT # 3
(inches)
XMIN .000E+00
XMAX 4.862E+02
YMIN -1.281E-01
YMAX 9.656E-02
Time (sec)
ABAQUS
LVDT4
Up/downsteam
Displacement
Input Motion SHAKEA
LVDT # 4
(inches)
XMIN .000E+00
XMAX 4.862E+02
YMIN -1.285E-01
YMAX 9.738E-02
Time (sec)

Figure C4

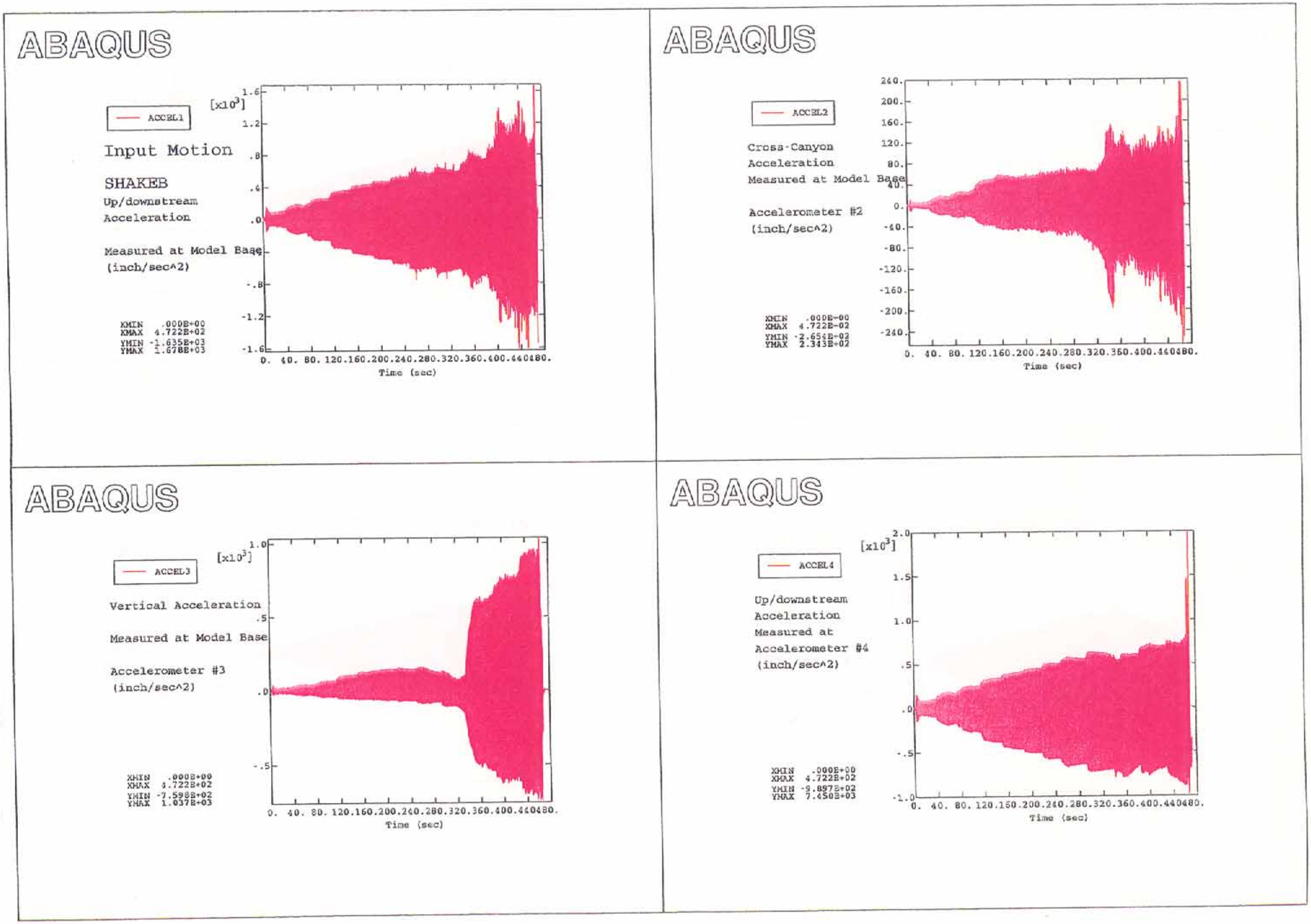
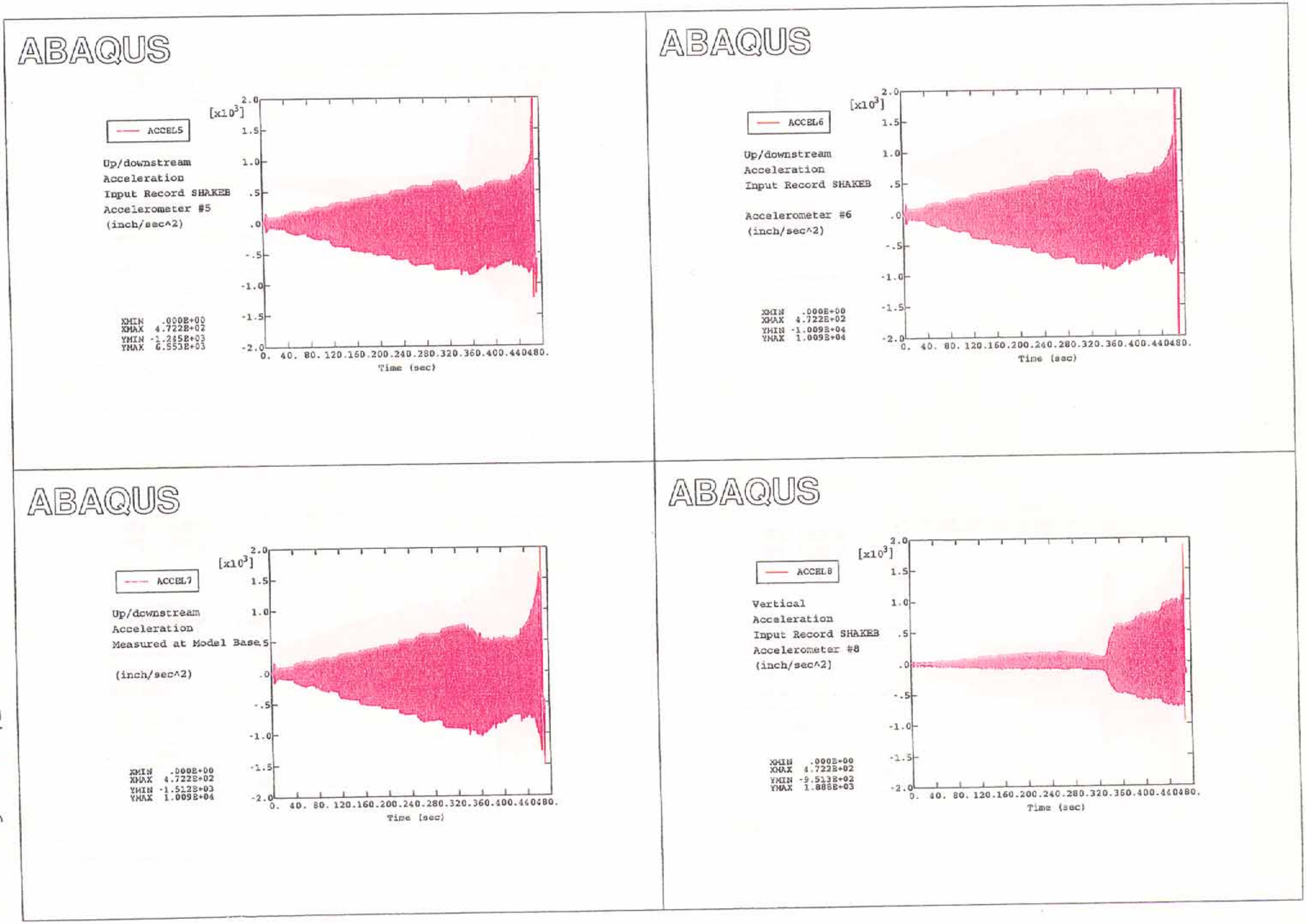

ABAQUS
ACCEL1
Input Motion
SHAKEB
Up/downstream
Acceleration
Measured at Model Base
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.635E+03
YMAX 1.678E+03
[x10^3]
Time (sec)
ABAQUS
ACCEL2
Cross-Canyon
Acceleration
Measured at Model Base
Accelerometer #2
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -2.654E+02
YMAX 2.343E+02
Time (sec)
ABAQUS
ACCEL3
Vertical Acceleration
Measured at Model Base
Accelerometer #3
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -7.598E+02
YMAX 1.037E+03
[x10^3]
Time (sec)
ABAQUS
ACCEL4
Up/downstream
Acceleration
Measured at
Accelerometer #4
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -9.897E+02
YMAX 7.450E+03
[x10^3]
Time (sec)

Figure C5



ABAQUS
ACCEL5
Up/downstream
Acceleration
Input Record SHAKEB
Accelerometer #5
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.245E+03
YMAX 6.553E+03
[x10^3]
Time (sec)
ABAQUS
ACCEL6
Up/downstream
Acceleration
Input Record SHAKEB
Accelerometer #6
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.009E+04
YMAX 1.009E+04
[x10^3]
Time (sec)
ABAQUS
ACCEL7
Up/downstream
Acceleration
Measured at Model Base
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.512E+03
YMAX 1.009E+04
[x10^3]
Time (sec)
ABAQUS
ACCEL8
Vertical
Acceleration
Input Record SHAKEB
Accelerometer #8
(inch/sec^2)
XMIN .000E+00
XMAX 4.722E+02
YMIN -9.513E+02
YMAX 1.888E+03
[x10^3]
Time (sec)

Figure C6

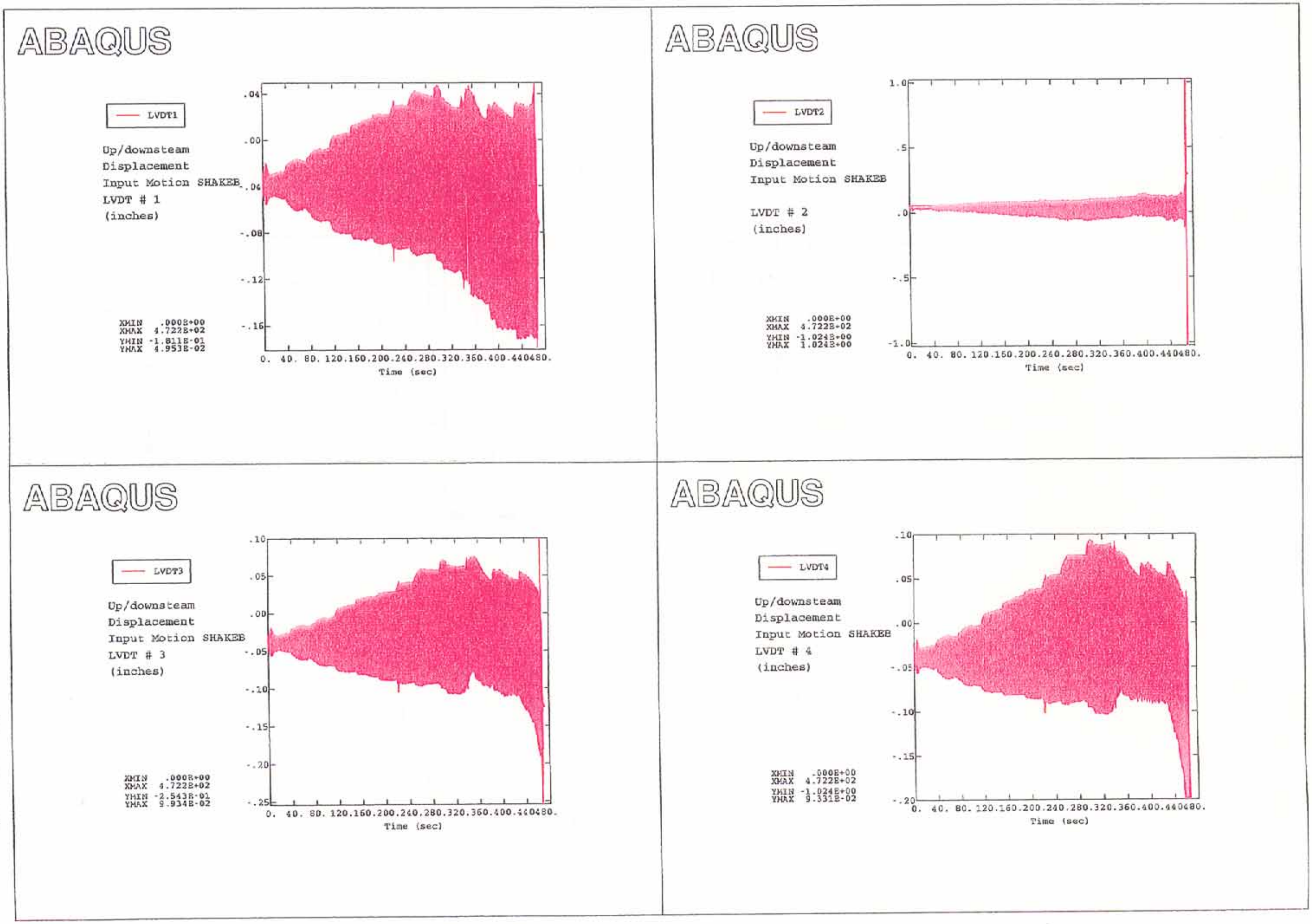

ABAQUS
LVDT1
Up/downsteam
Displacement
Input Motion SHAKEB
LVDT # 1
(inches)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.811E-01
YMAX 4.953E-02
Time (sec)
ABAQUS
LVDT2
Up/downsteam
Displacement
Input Motion SHAKEB
LVDT # 2
(inches)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.024E+00
YMAX 1.024E+00
Time (sec)
ABAQUS
LVDT3
Up/downsteam
Displacement
Input Motion SHAKEB
LVDT # 3
(inches)
XMIN .000E+00
XMAX 4.722E+02
YMIN -2.543E-01
YMAX 9.934E-02
Time (sec)
ABAQUS
LVDT4
Up/downsteam
Displacement
Input Motion SHAKEB
LVDT # 4
(inches)
XMIN .000E+00
XMAX 4.722E+02
YMIN -1.024E+00
YMAX 9.331E-02
Time (sec)

Figure C7

Koyna Laboratory Model Test
Final Cracking Pattern

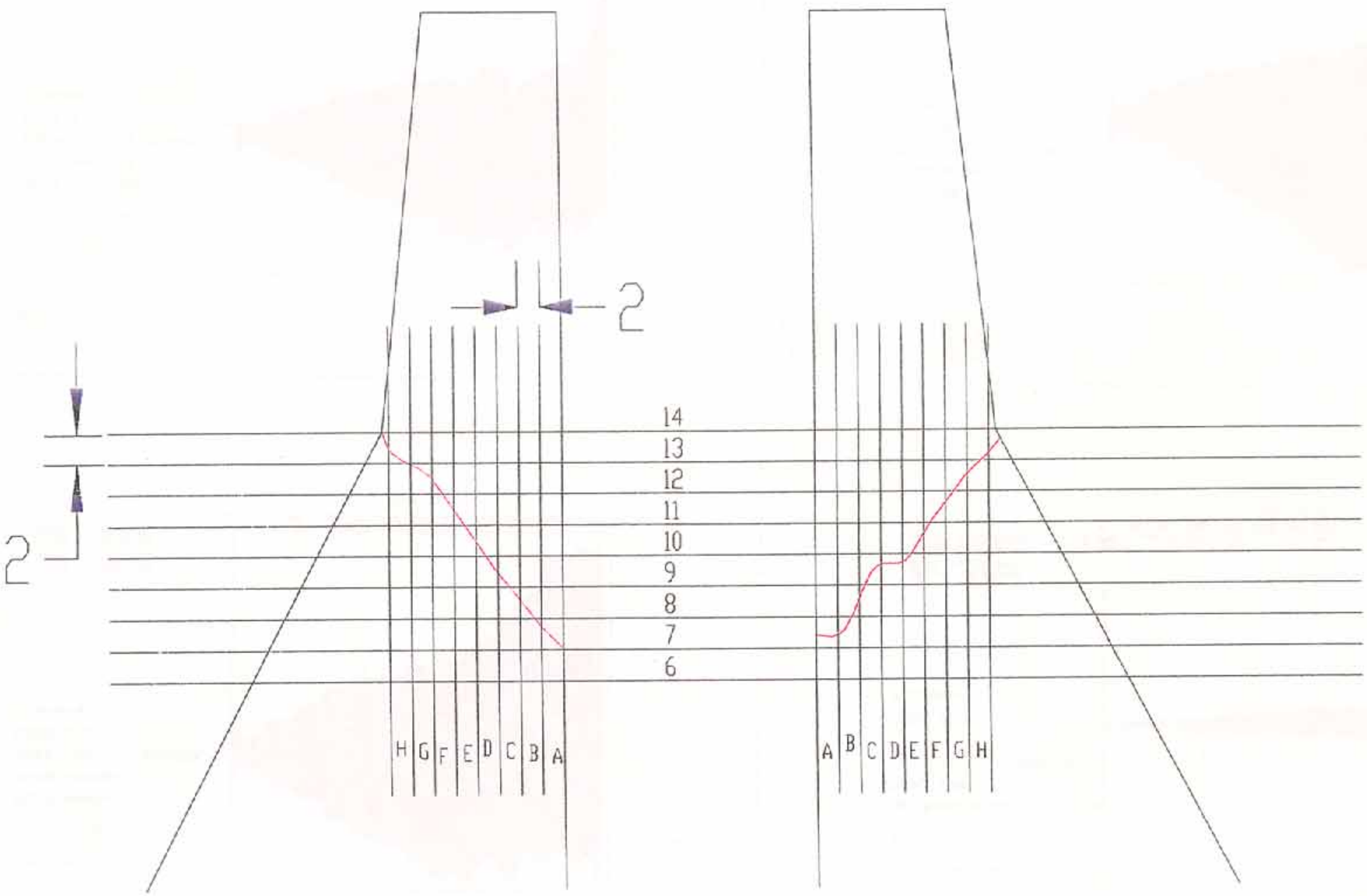


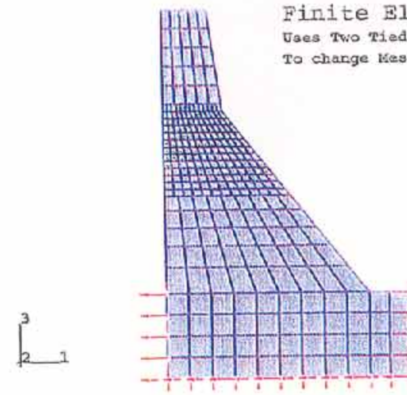
Figure C8

ABAQUS

Koyna Laboratory Model Study
Uncracked Model Study
Used to Evaluate
Linear and Non-linear
Material Propertys
For
ABAQUS STANDARD & EXPLICIT

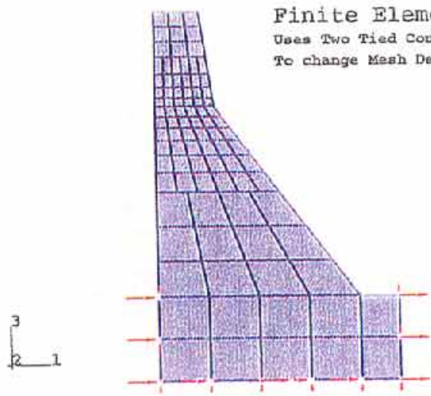
Determination of Mesh Sensitivity
Non-linear Material Propertys
Failure Stress = 55 psi
Mode I Fracture Energy = 0.2012
Crack Opening Strain = .001375

ABAQUS



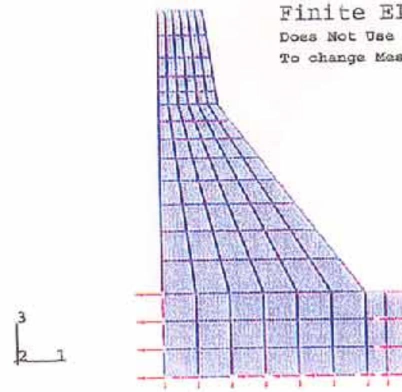
Finite Element Mesh #1
Uses Two Tied Contact Surfaces
To change Mesh Density

ABAQUS



Finite Element Mesh #2
Uses Two Tied Contact Surfaces
To change Mesh Density

ABAQUS



Finite Element Mesh #3
Does Not Use Tied Contact Surfaces
To change Mesh Density

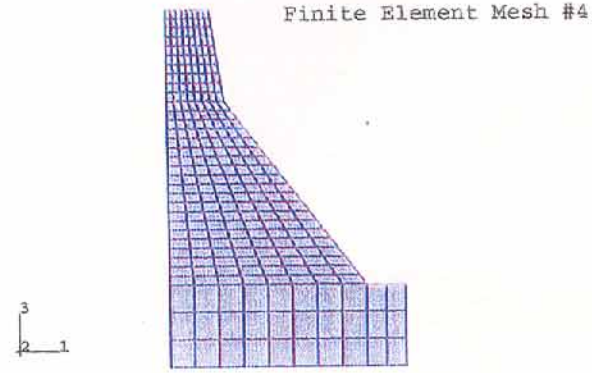
Figure d1

ABAQUS

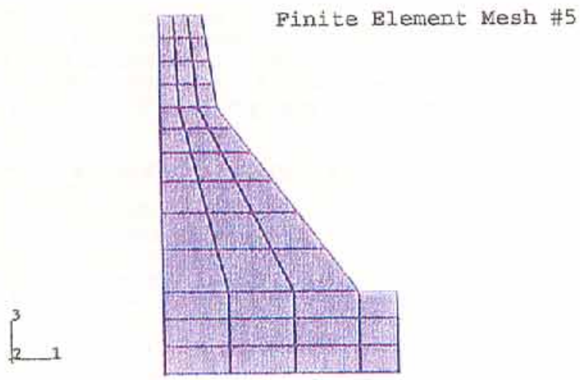
Koyna Laboratory Model Study
Uncracked Model Study
Used to Evaluate
Linear and Non-linear
Material Propertys
For
ABAQUS STANDARD & EXPLICIT

Determination of Mesh Sensitivity

ABAQUS



ABAQUS



ABAQUS

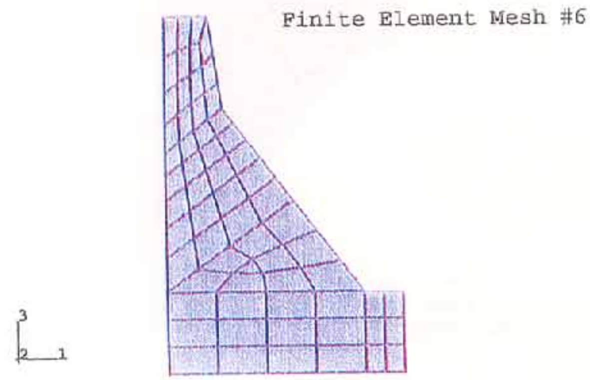


Figure d2

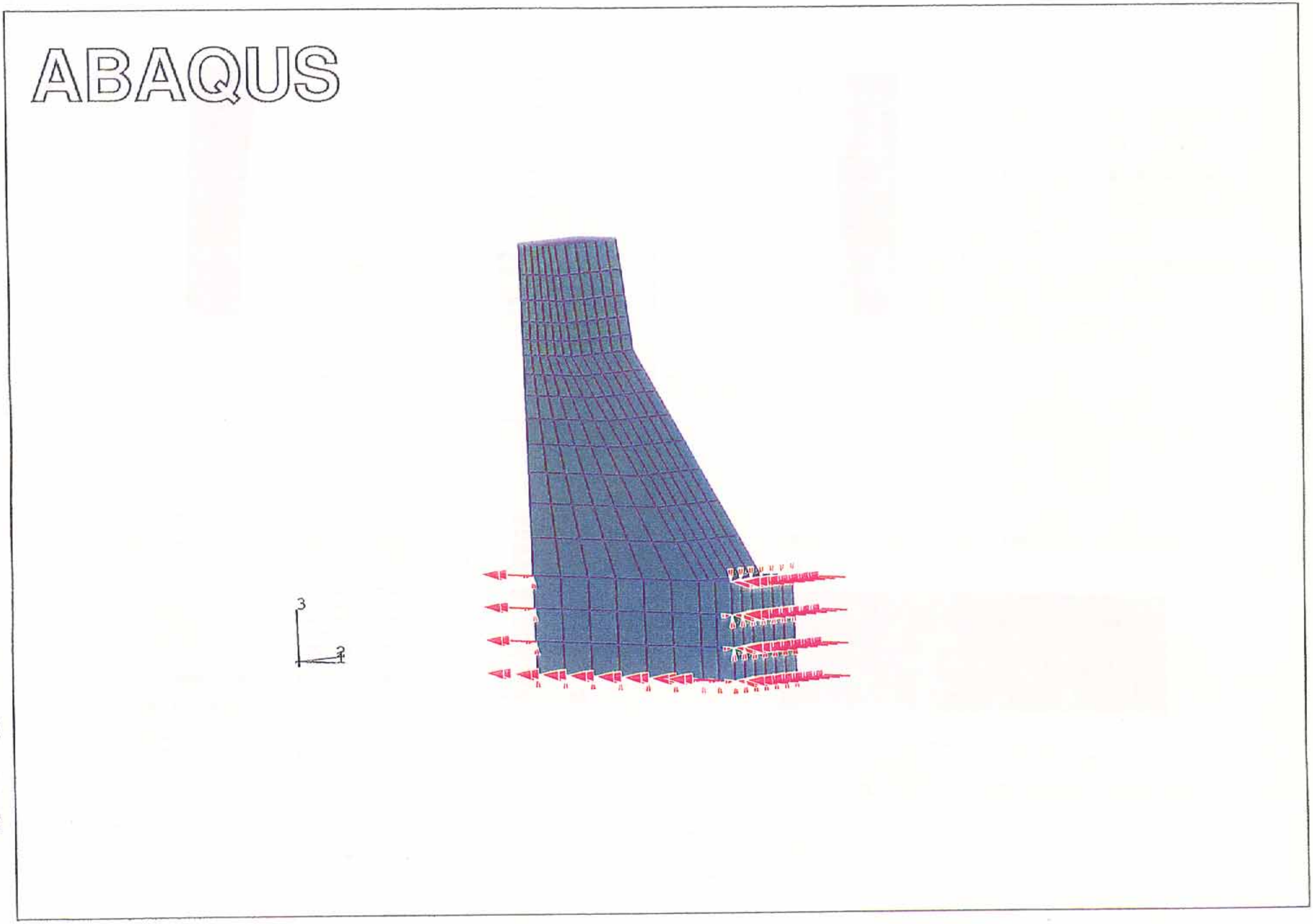


Figure d3

ABAQUS

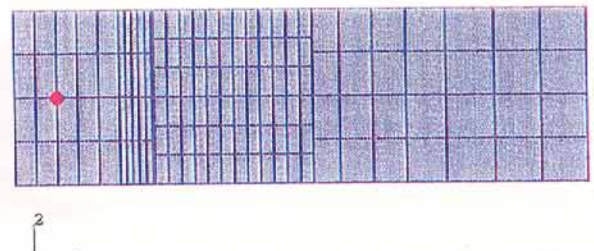
Koyna Laboratory Model Study
Locations of Instrumentation
Uncracked Model Study

Laboratory Test Model

Instrument	Elevation	Face	Corresponding Node
Accel04	49.6 inches	Upstream	503
Accel05	71.5 inches	Upstream	1534
Accel06	81.6 inches	Upstream	1955
Accel07	103.6 inches	Upstream	2075
Accel08	103.6 inches	Top	2085
LVDT01	23.6 inches	Downstream	298
LVDT02	49.6 inches	Upstream	503
LVDT03	61.6 inches	Downstream	1135
LVDT04	90.1 inches	Downstream	2010

ABAQUS

Location of Nodes in ABAQUS Model (Mesh #1)
Used for Comparisons
of Disp. and Accel. Time Histories
Vertical Accelerometer ACCEL08



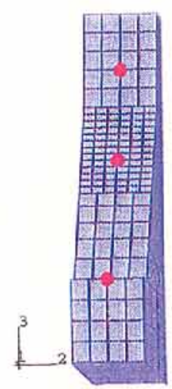
Plan View - Node 2085 - Center of Top Face

ABAQUS

Location of Nodes in
ABAQUS Model (Mesh #1)
Elev. View - Vertical Face
Used for Comparisons of
Disp. and Accel. Time Histories
Horizontal Accelerometers

Node	Elevation
2075	103.6 inches
1955	82.3 inches
1534	70.9 inches
503	50.9 inches

ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #1)
Elev. View
Downstream (Sloped) Face
Used for Comparisons of
Disp. and Accel. Time Histories

Horizontal LVDT's

Node	Elevation
2010	87.6 inches
1135	60.8 inches
298	23.6 inches

Figure d4

ABAQUS

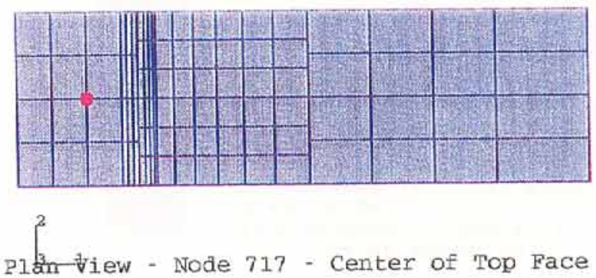
Koyna Laboratory Model Study
Locations of Instrumentation
Uncracked Model Study

Laboratory Test Model

Instrument	Elevation	Face	Corresponding Node
Accel04	49.6 inches	Upstream	118
Accel05	71.5 inches	Upstream	267
Accel06	81.6 inches	Upstream	610
Accel07	103.6 inches	Upstream	707
Accel08	103.6 inches	Top	717
LVDT01	23.6 inches	Downstream	8
LVDT02	49.6 inches	Upstream	118
LVDT03	61.6 inches	Downstream	407
LVDT04	90.1 inches	Downstream	762

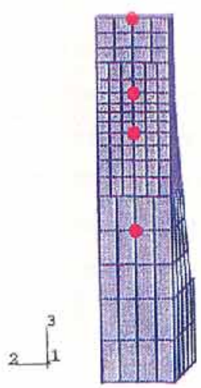
ABAQUS

Location of Nodes in ABAQUS Model (Mesh #2)
Used for Comparisons
of Disp. and Accel. Time Histories
Vertical Accelerometer ACCEL08



Plan View - Node 717 - Center of Top Face

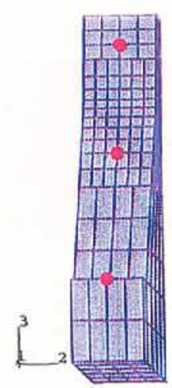
ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #2)
Elev. View - Vertical Face
Used for Comparisons of
Disp. and Accel. Time Histories
Horizontal Accelerometers

Node	Elevation
707	103.6 inches
610	82.3 inches
267	70.9 inches
118	43.1 inches

ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #2)
Elev. View
Downstream (Sloped) Face
Used for Comparisons of
Disp. and Accel. Time Histories

Horizontal LVDT's

Node	Elevation
762	95.1 inches
407	63.2 inches
8	23.6 inches

Figure d5

ABAQUS

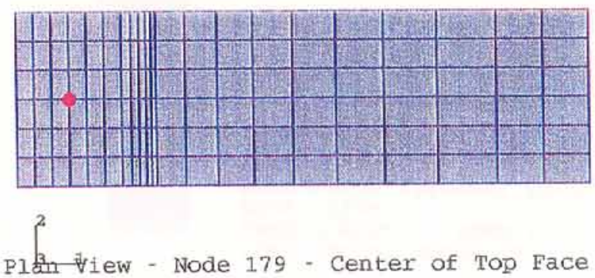
Koyna Laboratory Model Study
Locations of Instrumentation
Uncracked Model Study

Laboratory Test Model

Instrument	Elevation	Face	Corresponding Node
Accel04	49.6 inches	Upstream	519
Accel05	71.5 inches	Upstream	419
Accel06	81.6 inches	Upstream	204
Accel07	103.6 inches	Upstream	176
Accel08	103.6 inches	Top	179
LVDT01	23.6 inches	Downstream	859
LVDT02	49.6 inches	Upstream	519
LVDT03	61.6 inches	Downstream	511
LVDT04	90.1 inches	Downstream	196

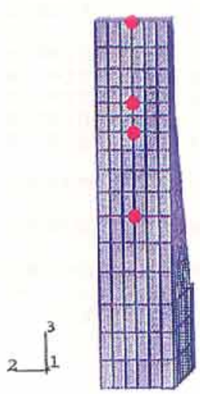
ABAQUS

Location of Nodes in ABAQUS Model (Mesh#3)
Used for Comparisons
of Disp. and Accel. Time Histories
Vertical Accelerometer ACCEL08



Plan View - Node 179 - Center of Top Face

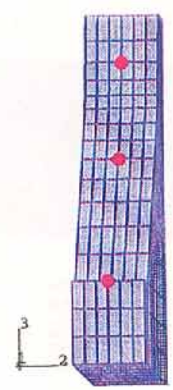
ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #3)
Elev. View - Vertical Face
Used for Comparisons of
Disp. and Accel. Time Histories
Horizontal Accelerometers

Node	Elevation
176	103.6 inches
204	80.6 inches
491	72.3 inches
519	48.6 inches

ABAQUS



Location of Nodes in
ABAQUS Model (Mesh#3)
Elev. View
Downstream (Sloped) Face
Used for Comparisons of
Disp. and Accel. Time Histories

Horizontal LVDT's

Node	Elevation
196	90.1 inches
511	61.6 inches
859	23.6 inches

Figure d6

ABAQUS

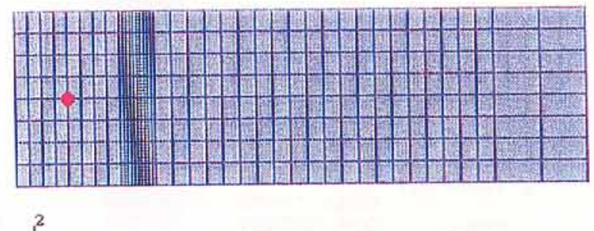
Koyna Laboratory Model Study
Locations of Instrumentation
Uncracked Model Study

Laboratory Test Model

Instrument	Elevation	Face	Corresponding Node
Accel04	49.6 inches	Upstream	118
Accel05	71.5 inches	Upstream	267
Accel06	81.6 inches	Upstream	610
Accel07	103.6 inches	Upstream	707
Accel08	103.6 inches	Top	717
LVDT01	23.6 inches	Downstream	8
LVDT02	49.6 inches	Upstream	118
LVDT03	61.6 inches	Downstream	407
LVDT04	90.1 inches	Downstream	762

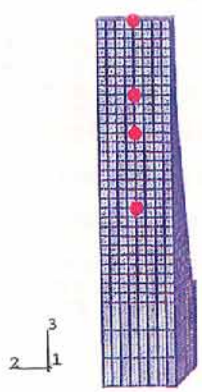
ABAQUS

Location of Nodes in ABAQUS Model (Mesh #4)
Used for Comparisons
of Disp. and Accel. Time Histories
Vertical Accelerometer ACCEL08



Plan View - Node 401 - Center of Top Face

ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #2)
Elev. View - Vertical Face
Used for Comparisons of
Disp. and Accel. Time Histories
Horizontal Accelerometers

Node	Elevation
397	103.6 inches
469	82.2 inches
1621	71.6 inches
1693	50.3 inches

ABAQUS

Location of Nodes in
ABAQUS Model (Mesh #4)
Elev. View
Downstream (Sloped) Face
Used for Comparisons of
Disp. and Accel. Time Histories

Horizontal LVDT's

Node	Elevation
450	90.3 inches
1665	60.9 inches
2788	23.6 inches

Figure d7

ABAQUS

Koyna Laboratory Model Study
Locations of Instrumentation

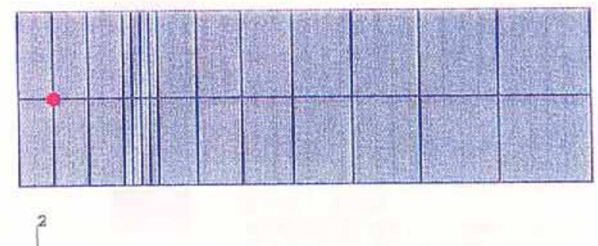
Uncracked Model Study

Laboratory Test Model

Instrument	Elevation	Face	Corresponding Node
Accel04	49.6 inches	Upstream	118
Accel05	71.5 inches	Upstream	267
Accel06	81.6 inches	Upstream	610
Accel07	103.6 inches	Upstream	707
Accel08	103.6 inches	Top	717
LVDT01	23.6 inches	Downstream	8
LVDT02	49.6 inches	Upstream	118
LVDT03	61.6 inches	Downstream	407
LVDT04	90.1 inches	Downstream	762

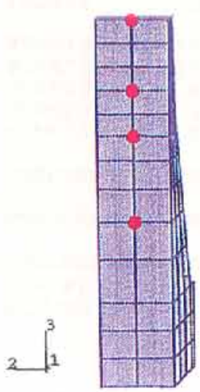
ABAQUS

Location of Nodes in ABAQUS Model (Mesh #5)
Used for Comparisons
of Disp. and Accel. Time Histories
Vertical Accelerometer ACCEL08



Plan View - Node 22 - Center of Top Face

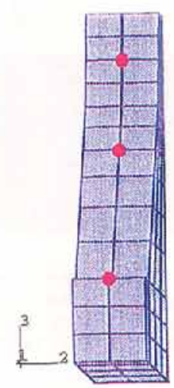
ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #5)
Elev. View - Vertical Face
Used for Comparisons of
Disp. and Accel. Time Histories
Horizontal Accelerometers

Node	Elevation
21	103.6 inches
33	83.6 inches
85	70.7 inches
97	46.4 inches

ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #5)
Elev. View
Downstream (Sloped) Face
Used for Comparisons of
Disp. and Accel. Time Histories

Horizontal LVDT's

Node	Elevation
32	90.3 inches
92	63.8 inches
173	23.6 inches

Figure d8

ABAQUS

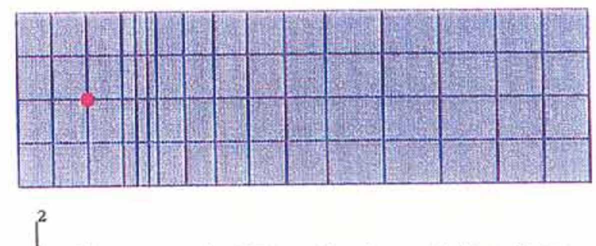
Koyna Laboratory Model Study
Locations of Instrumentation
Uncracked Model Study

Laboratory Test Model

Instrument	Elevation	Face	Corresponding Node
Accel04	49.6 inches	Upstream	196
Accel05	71.5 inches	Upstream	104
Accel06	81.6 inches	Upstream	124
Accel07	103.6 inches	Upstream	163
Accel08	103.6 inches	Top	165
LVDT01	23.6 inches	Downstream	289
LVDT02	49.6 inches	Upstream	196
LVDT03	61.6 inches	Downstream	232
LVDT04	90.1 inches	Downstream	140

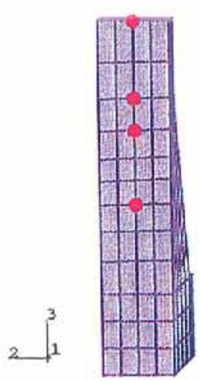
ABAQUS

Location of Nodes in ABAQUS Model (Mesh#6)
Used for Comparisons
of Disp. and Accel. Time Histories
Vertical Accelerometer ACCEL08



Plan View - Node 165 - Center of Top Face

ABAQUS



Location of Nodes in
ABAQUS Model (Mesh #6)
Elev. View - Vertical Face
Used for Comparisons of
Disp. and Accel. Time Histories
Horizontal Accelerometers

Node	Elevation
163	103.6 inches
124	80.8 inches
104	71.5 inches
196	49.8 inches

ABAQUS

Location of Nodes in
ABAQUS Model (Mesh#6)
Elev. View
Downstream (Sloped) Face
Used for Comparisons of
Disp. and Accel. Time Histories

Horizontal LVDT's

Node	Elevation
140	92.8 inches
232	62.5 inches
289	23.6 inches

Figure d9

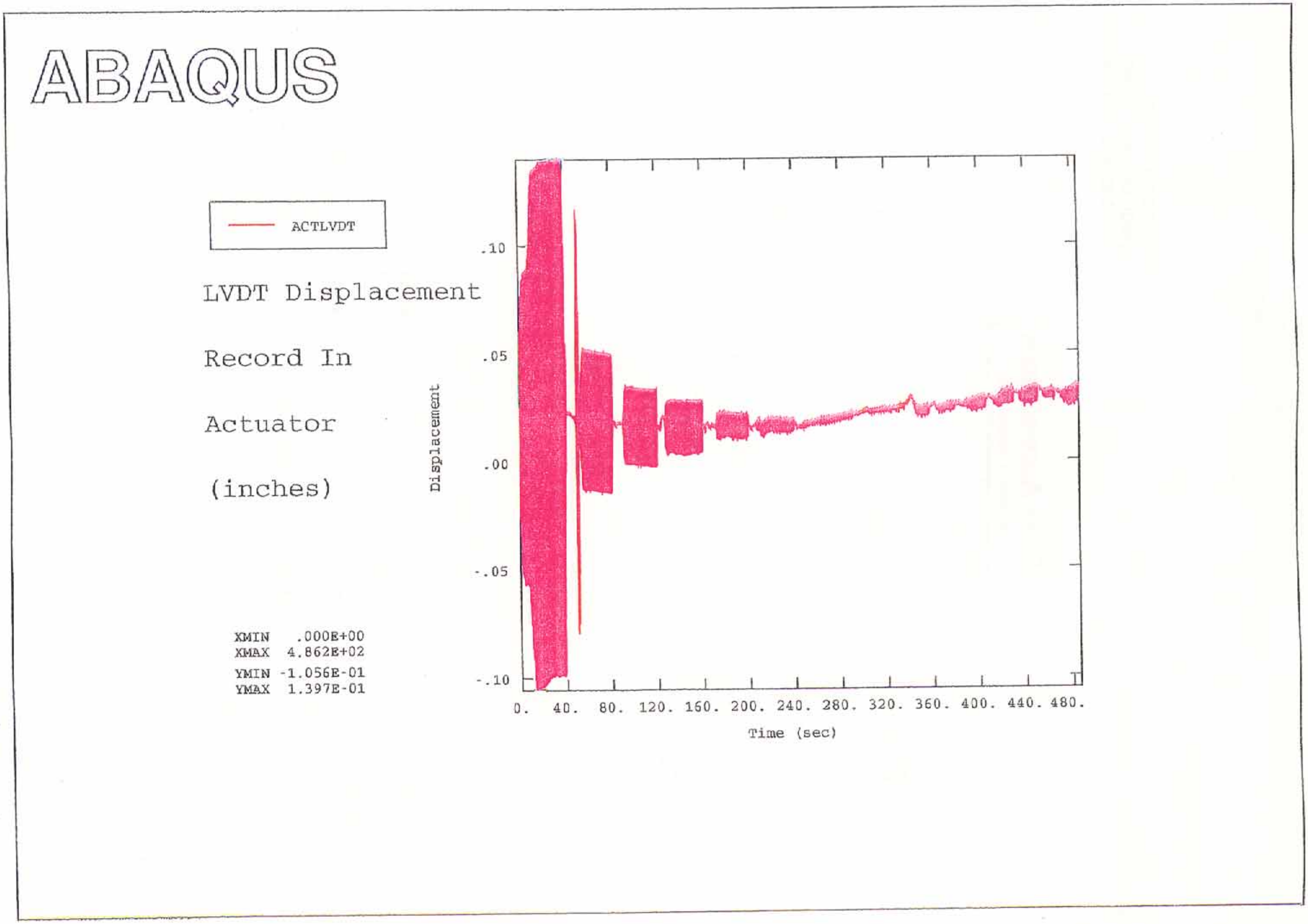

ABAQUS
ACTLVDT
LVDT Displacement
Record In
Actuator
(inches)
Displacement
.10
.05
.00
-.05
-.10
XMIN .000E+00
XMAX 4.862E+02
YMIN -1.056E-01
YMAX 1.397E-01
0. 40. 80. 120. 160. 200. 240. 280. 320. 360. 400. 440. 480.
Time (sec)

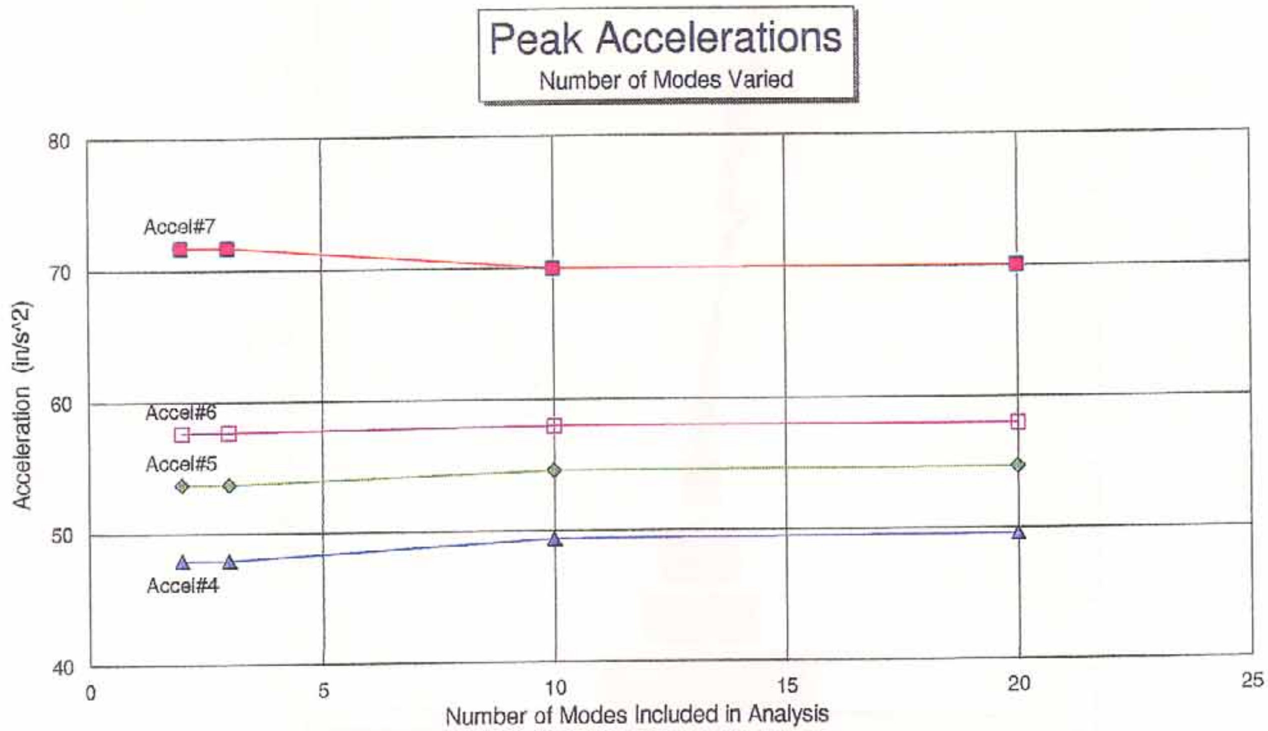
Figure e1

Uncracked Koyna Laboratory Study
Determination of the Number of Modes Required
Mesh#3

Material Properties

E = 150 ksi
Material Density = 138.2 pcf

Damping = 5% critical
Rayleigh Damping Factors
Alpha=2.827433,Beta=.000318



Peak Accelerations (inch / sec ^ 2)					
Number of Modes Used	2	3	10	20	LAB
Accel#7	71.71	71.71	69.98	69.99	53.26
Accel#6	57.60	57.66	57.99	57.99	51.72
Accel#5	53.67	53.67	54.55	54.64	49.26
Accel#4	47.89	47.89	49.35	49.56	47.72
CPU Time (sec)	53.04	56.91	163.21	210.94	

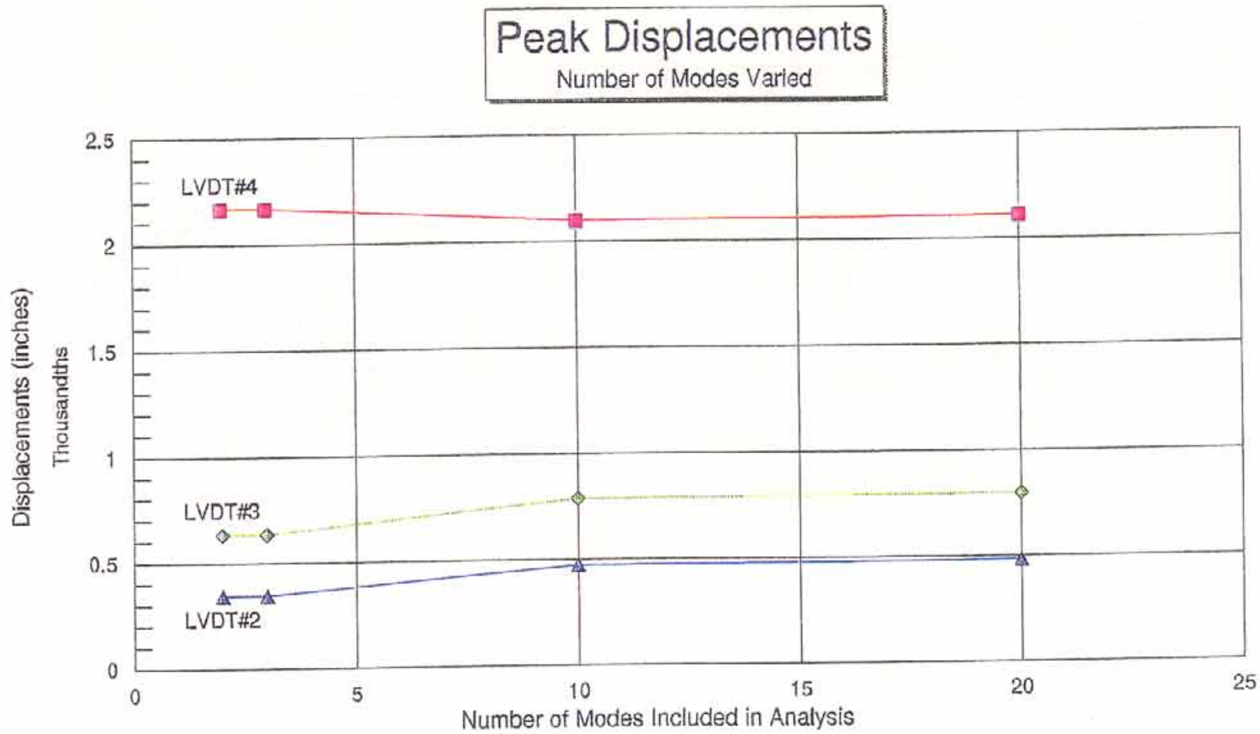
Figure e2

Uncracked Koyna Laboratory Study
Determination of the Number of Modes Required
Mesh#3

Material Properties

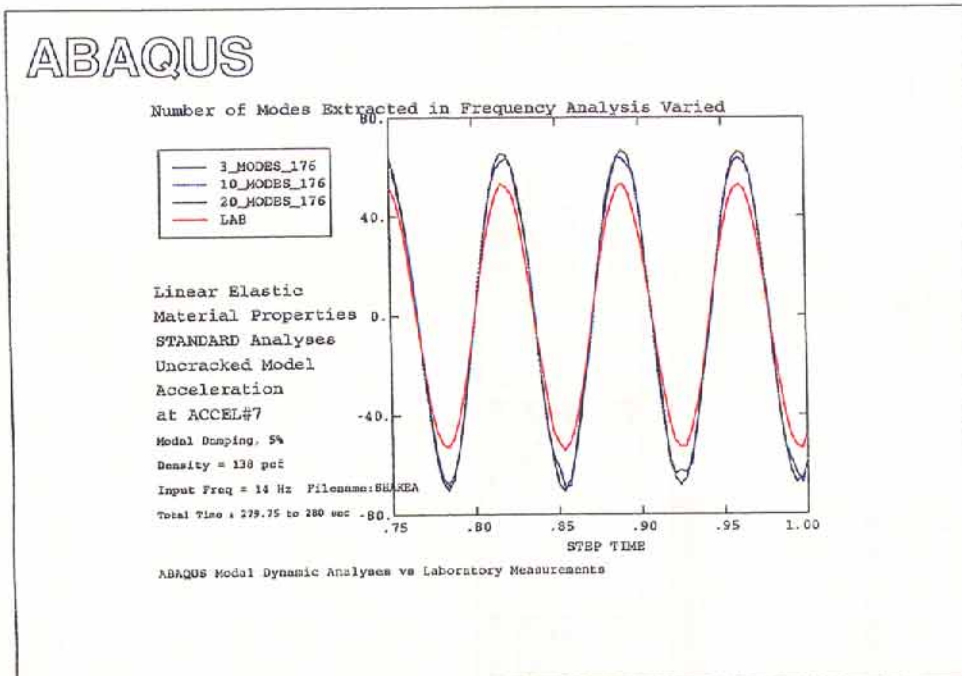
E = 150 ksi
Material Density = 138.2 pcf

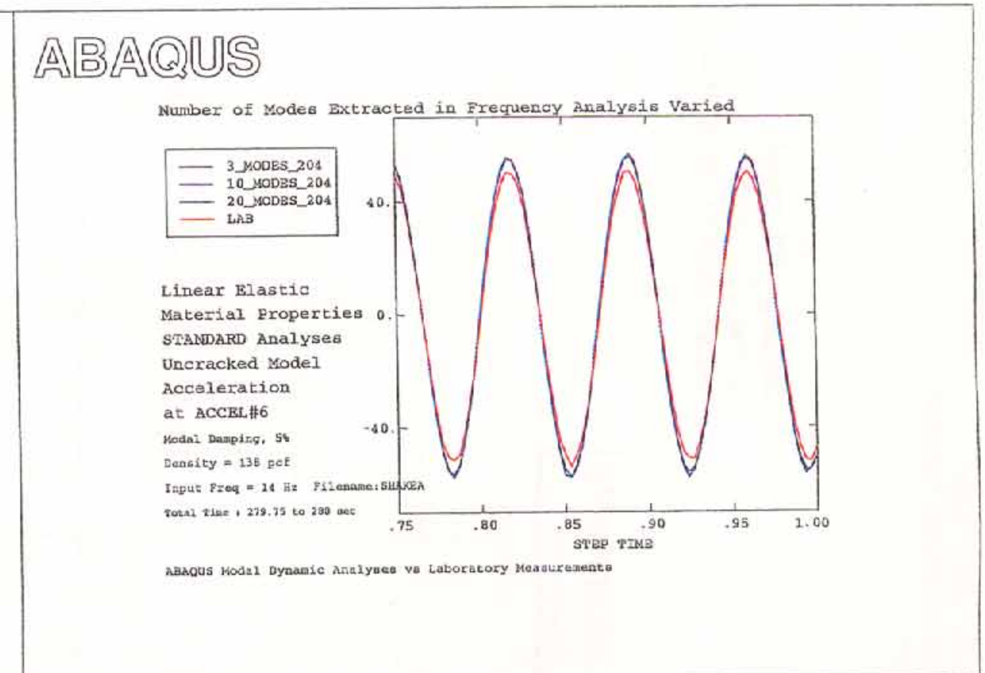
Damping = 5% critical
Rayleigh Damping Factors
Alpha=2.827433,Beta=.000318

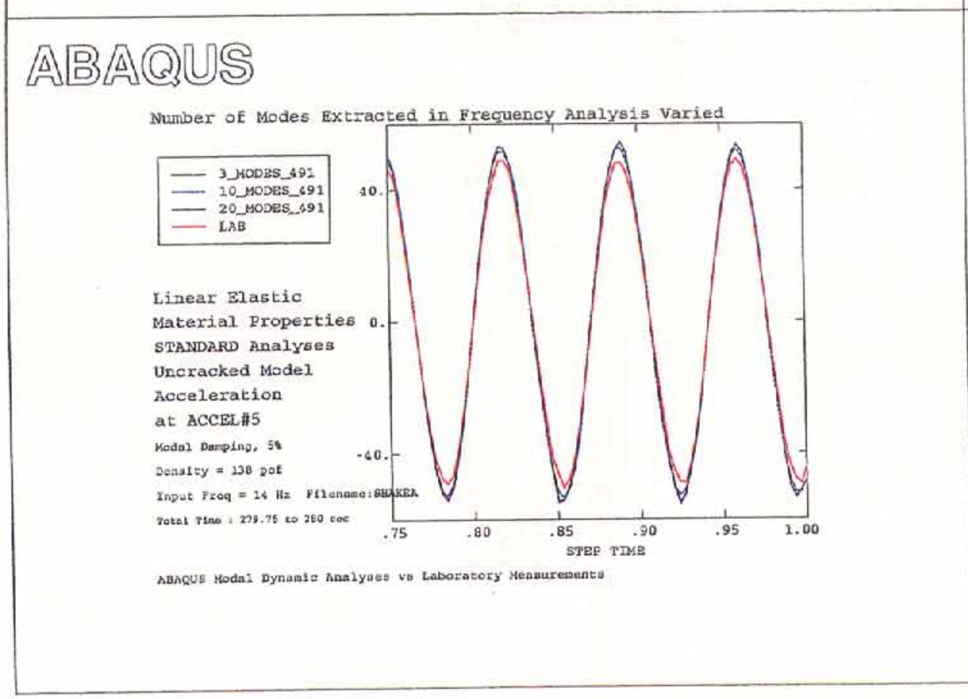


Peak Displacements (inches)					
Number of Modes Used	2	3	10	20	LAB
LVDT#4 LVDT#3 LVDT#2	2.2E-03 6.3E-04 3.4E-04	2.2E-03 6.3E-04 3.4E-04	2.1E-03 7.9E-04 4.7E-04	2.1E-03 7.9E-04 4.8E-04	7.2E-04 3.1E-04 2.1E-04

Figure e3


ABAQUS
Number of Modes Extracted in Frequency Analysis Varied
3_MODES_176
10_MODES_176
20_MODES_176
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Modal Damping, 5%
Density = 138 pcf
Input Freq = 14 Hz Filename:SHAKEA
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements


ABAQUS
Number of Modes Extracted in Frequency Analysis Varied
3_MODES_204
10_MODES_204
20_MODES_204
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Modal Damping, 5%
Density = 138 pcf
Input Freq = 14 Hz Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements


ABAQUS
Number of Modes Extracted in Frequency Analysis Varied
3_MODES_491
10_MODES_491
20_MODES_491
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Modal Damping, 5%
Density = 138 pcf
Input Freq = 14 Hz Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

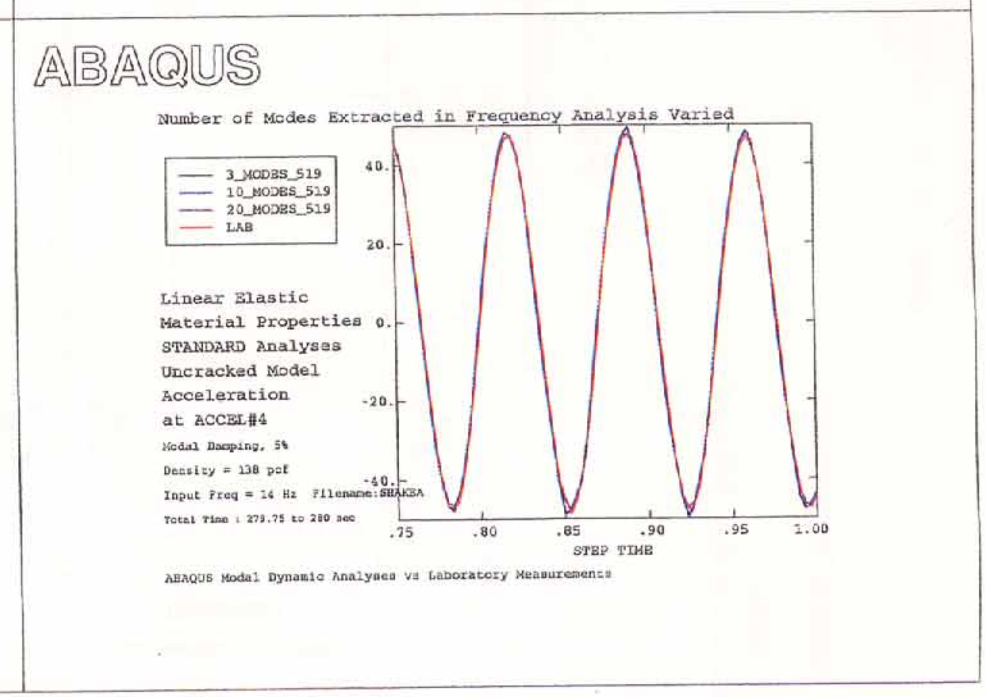
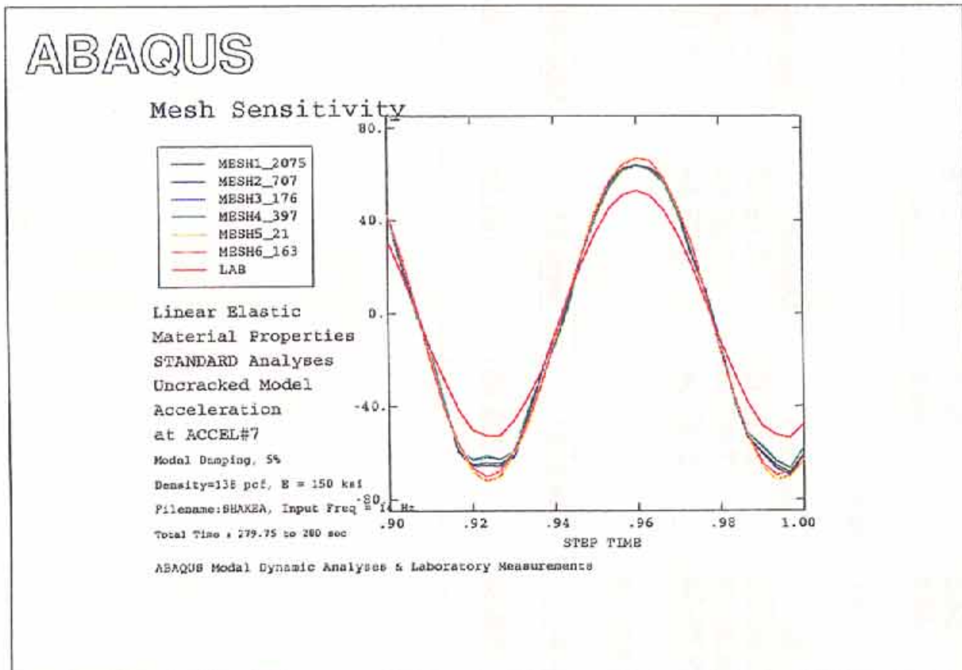
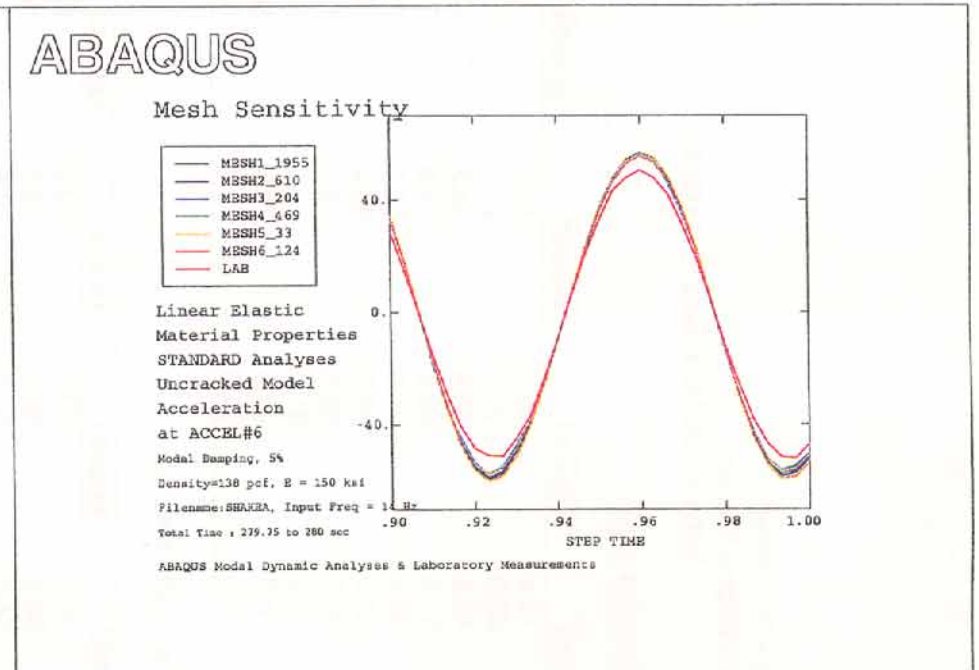
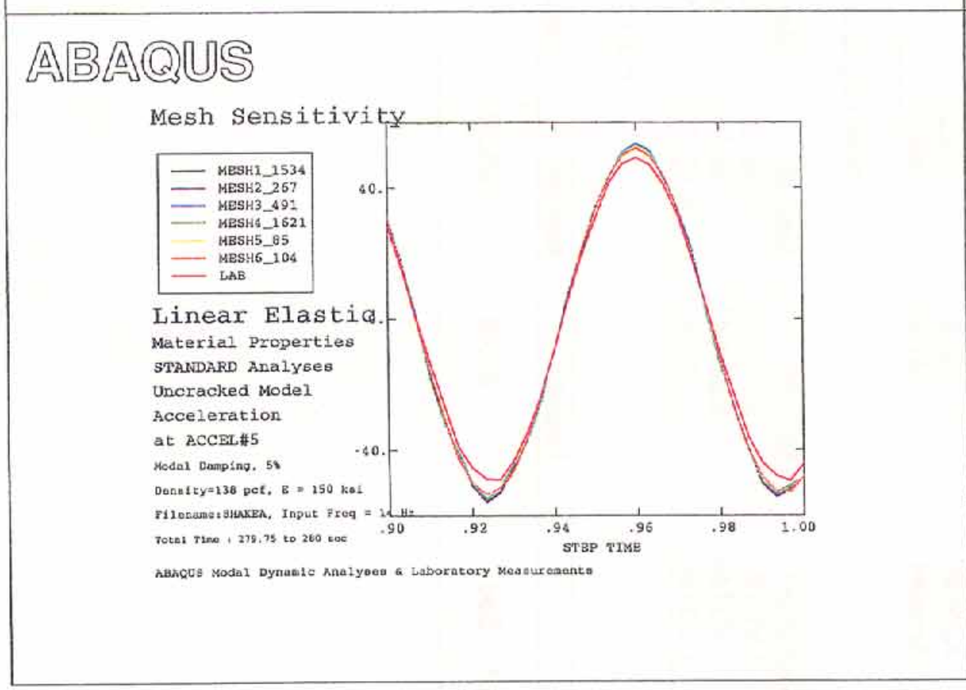

ABAQUS
Number of Modes Extracted in Frequency Analysis Varied
3_MODES_519
10_MODES_519
20_MODES_519
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Modal Damping, 5%
Density = 138 pcf
Input Freq = 14 Hz Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
20.
0.
-20.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

Figure e4


ABAQUS
Mesh Sensitivity
MESH1_2075
MESH2_707
MESH3_176
MESH4_397
MESH5_21
MESH6_163
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Modal Damping, 5%
Density=138 pcf, E = 150 ksi
Filename:SHAKEA, Input Freq = 14 Hz
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses & Laboratory Measurements


ABAQUS
Mesh Sensitivity
MESH1_1955
MESH2_610
MESH3_204
MESH4_469
MESH5_33
MESH6_124
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Modal Damping, 5%
Density=138 pcf, E = 150 ksi
Filename:SHAKEA, Input Freq = 14 Hz
Total Time : 279.75 to 280 sec
40.
0.
-40.
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses & Laboratory Measurements


ABAQUS
Mesh Sensitivity
MESH1_1534
MESH2_257
MESH3_491
MESH4_1621
MESH5_85
MESH6_104
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Modal Damping, 5%
Density=138 pcf, E = 150 ksi
Filename:SHAKEA, Input Freq = 14 Hz
Total Time : 279.75 to 280 sec
40.
0.
-40.
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses & Laboratory Measurements

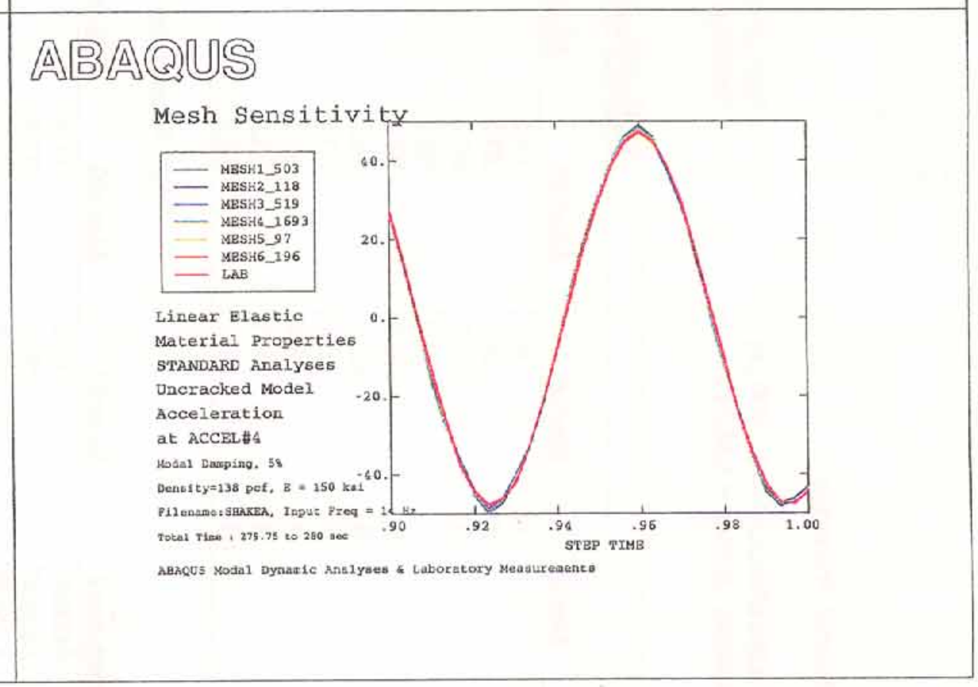

ABAQUS
Mesh Sensitivity
MESH1_503
MESH2_118
MESH3_519
MESH4_1693
MESH5_97
MESH6_196
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Modal Damping, 5%
Density=138 pcf, E = 150 ksi
Filename:SHAKEA, Input Freq = 14 Hz
Total Time : 279.75 to 280 sec
40.
20.
0.
-20.
-40.
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses & Laboratory Measurements

Figure f2

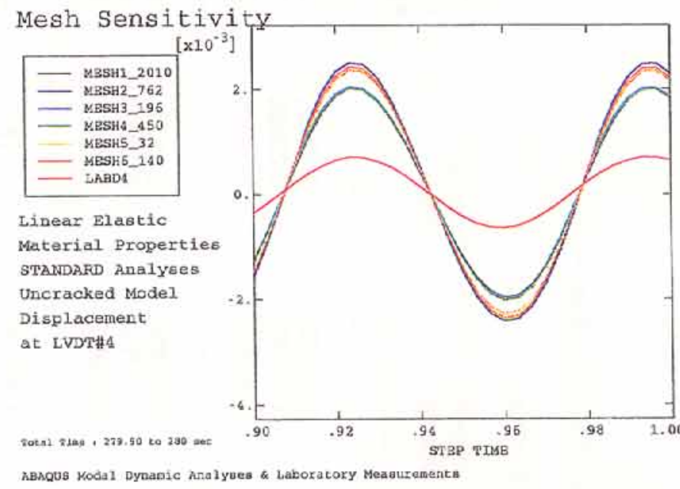
ABAQUS

Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Mesh Density

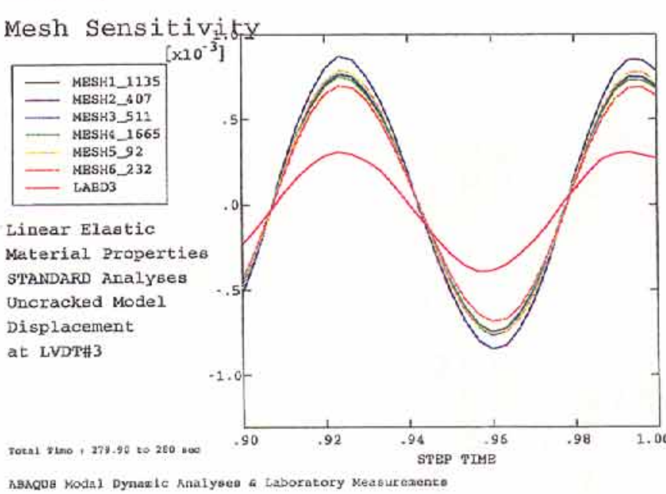
Comparison of Displacements
ABAQUS STANDARD
Modal Dynamic Analysis

Input Record SHAKEA
Modal Damping, 3.5%
Elastic Modulus = 150 ksi
Density = 138.2 pcf

ABAQUS



ABAQUS



ABAQUS

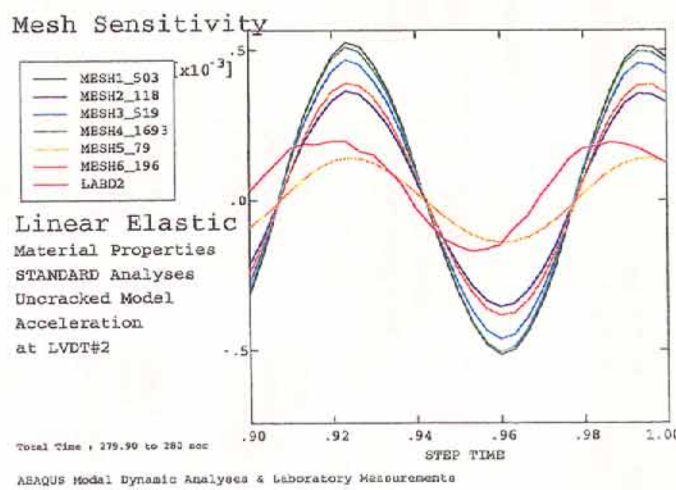


Figure f3

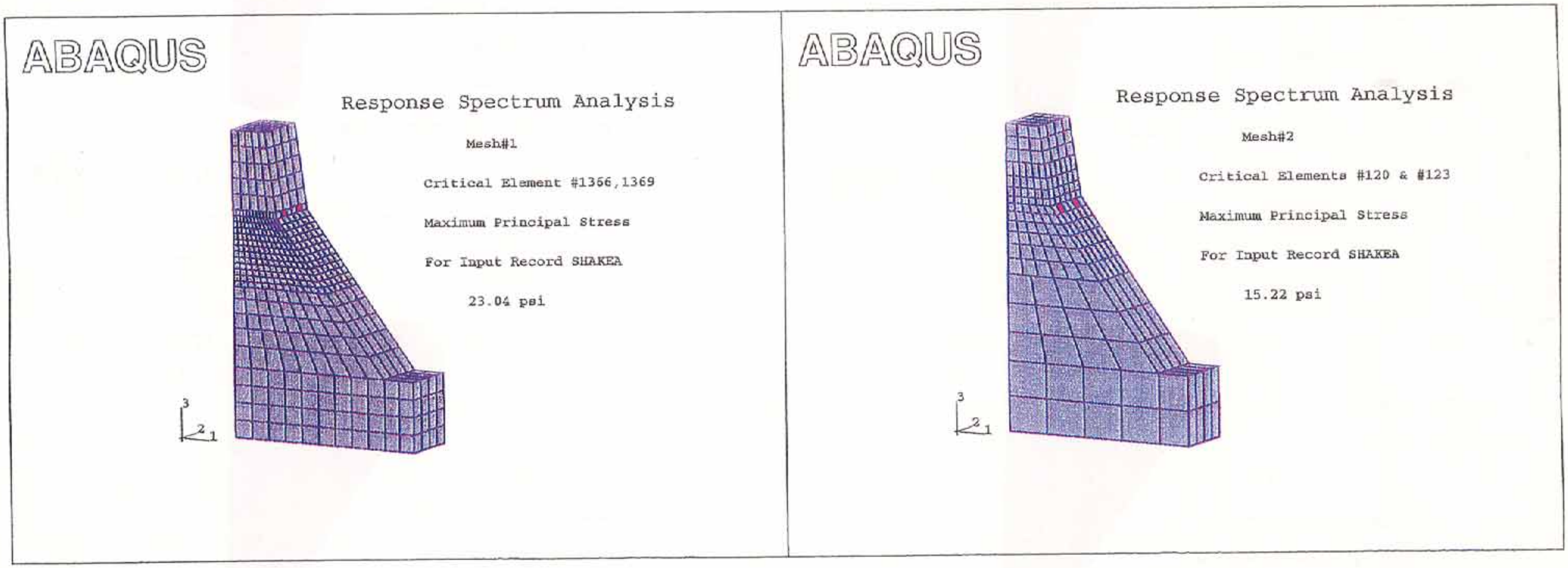

ABAQUS
Response Spectrum Analysis
Mesh#1
Critical Element #1366,1369
Maximum Principal Stress
For Input Record SHAKEA
23.04 psi
ABAQUS
Response Spectrum Analysis
Mesh#2
Critical Elements #120 & #123
Maximum Principal Stress
For Input Record SHAKEA
15.22 psi

Figure f5

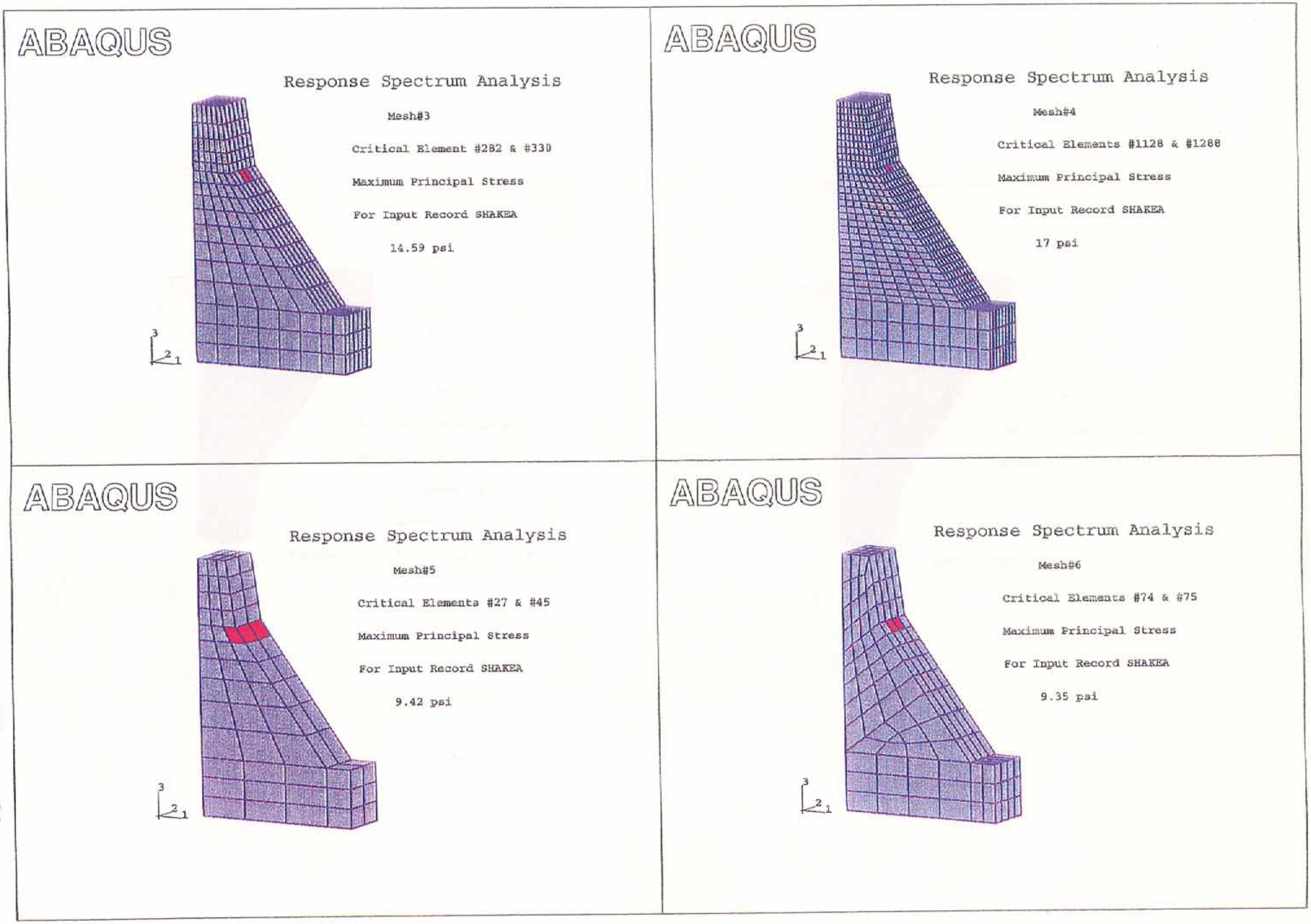

ABAQUS
Response Spectrum Analysis
Mesh#3
Critical Element #282 & #330
Maximum Principal Stress
For Input Record SHAKEA
14.59 psi
ABAQUS
Response Spectrum Analysis
Mesh#4
Critical Elements #1128 & #1288
Maximum Principal Stress
For Input Record SHAKEA
17 psi
ABAQUS
Response Spectrum Analysis
Mesh#5
Critical Elements #27 & #45
Maximum Principal Stress
For Input Record SHAKEA
9.42 psi
ABAQUS
Response Spectrum Analysis
Mesh#6
Critical Elements #74 & #75
Maximum Principal Stress
For Input Record SHAKEA
9.35 psi

Figure f6

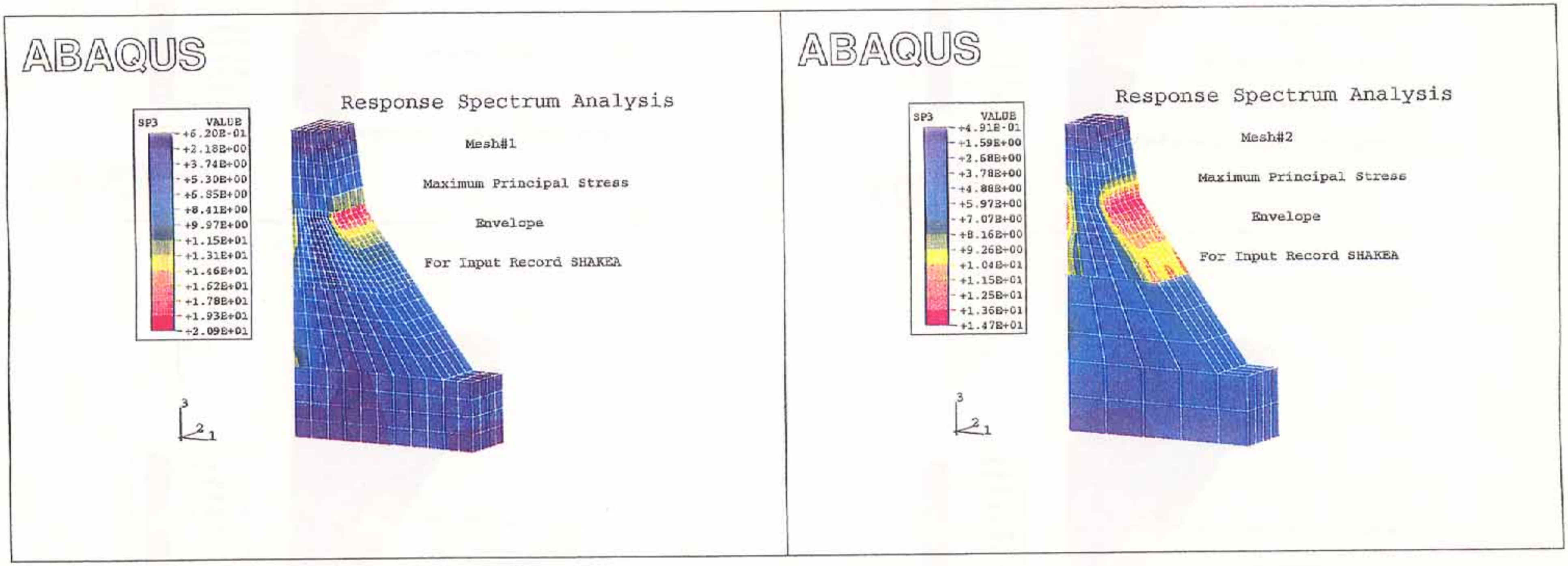

ABAQUS
Response Spectrum Analysis
Mesh#1
Maximum Principal Stress
Envelope
For Input Record SHAKEA
SP3 VALUE
+6.20E-01
+2.18E+00
+3.74E+00
+5.30E+00
+6.85E+00
+8.41E+00
+9.97E+00
+1.15E+01
+1.31E+01
+1.46E+01
+1.62E+01
+1.78E+01
+1.93E+01
+2.09E+01
ABAQUS
Response Spectrum Analysis
Mesh#2
Maximum Principal Stress
Envelope
For Input Record SHAKEA
SP3 VALUE
+4.91E-01
+1.59E+00
+2.68E+00
+3.78E+00
+4.88E+00
+5.97E+00
+7.07E+00
+8.16E+00
+9.26E+00
+1.04E+01
+1.15E+01
+1.25E+01
+1.36E+01
+1.47E+01

Figure f7

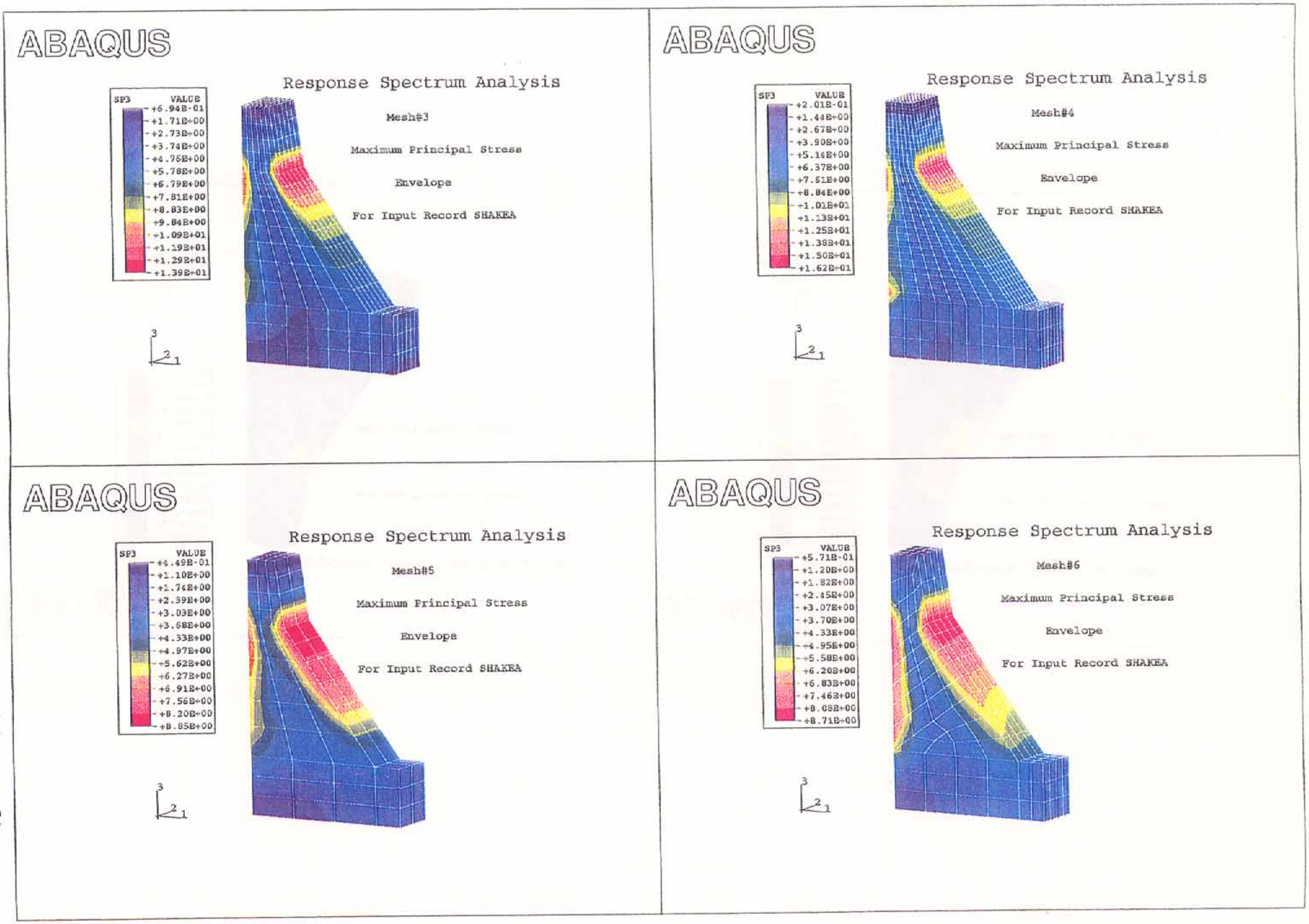

ABAQUS
Response Spectrum Analysis
SP3 VALUE
+6.94E-01
+1.71E+00
+2.73E+00
+3.74E+00
+4.76E+00
+5.78E+00
+6.79E+00
+7.81E+00
+8.83E+00
+9.84E+00
+1.09E+01
+1.19E+01
+1.29E+01
+1.39E+01
Mesh#3
Maximum Principal Stress
Envelope
For Input Record SHAKEA
3
2
1
ABAQUS
Response Spectrum Analysis
SP3 VALUE
+2.01E-01
+1.44E+00
+2.67E+00
+3.90E+00
+5.14E+00
+6.37E+00
+7.61E+00
+8.84E+00
+1.01E+01
+1.13E+01
+1.25E+01
+1.38E+01
+1.50E+01
+1.62E+01
Mesh#4
Maximum Principal Stress
Envelope
For Input Record SHAKEA
3
2
1
ABAQUS
Response Spectrum Analysis
SP3 VALUE
+4.49E-01
+1.10E+00
+1.74E+00
+2.39E+00
+3.03E+00
+3.68E+00
+4.33E+00
+4.97E+00
+5.62E+00
+6.27E+00
+6.91E+00
+7.56E+00
+8.20E+00
+8.85E+00
Mesh#5
Maximum Principal Stress
Envelope
For Input Record SHAKEA
3
2
1
ABAQUS
Response Spectrum Analysis
SP3 VALUE
+5.71E-01
+1.20E+00
+1.82E+00
+2.45E+00
+3.07E+00
+3.70E+00
+4.33E+00
+4.95E+00
+5.58E+00
+6.20E+00
+6.83E+00
+7.46E+00
+8.08E+00
+8.71E+00
Mesh#6
Maximum Principal Stress
Envelope
For Input Record SHAKEA
3
2
1

Figure f8

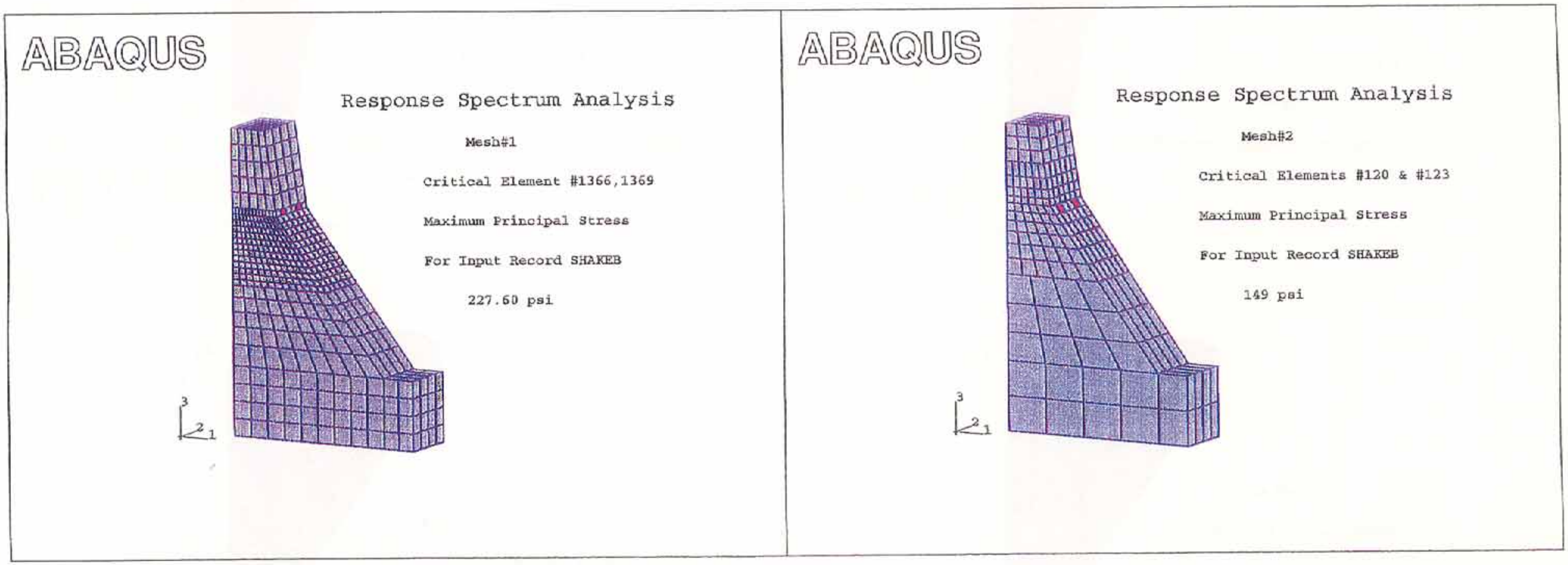
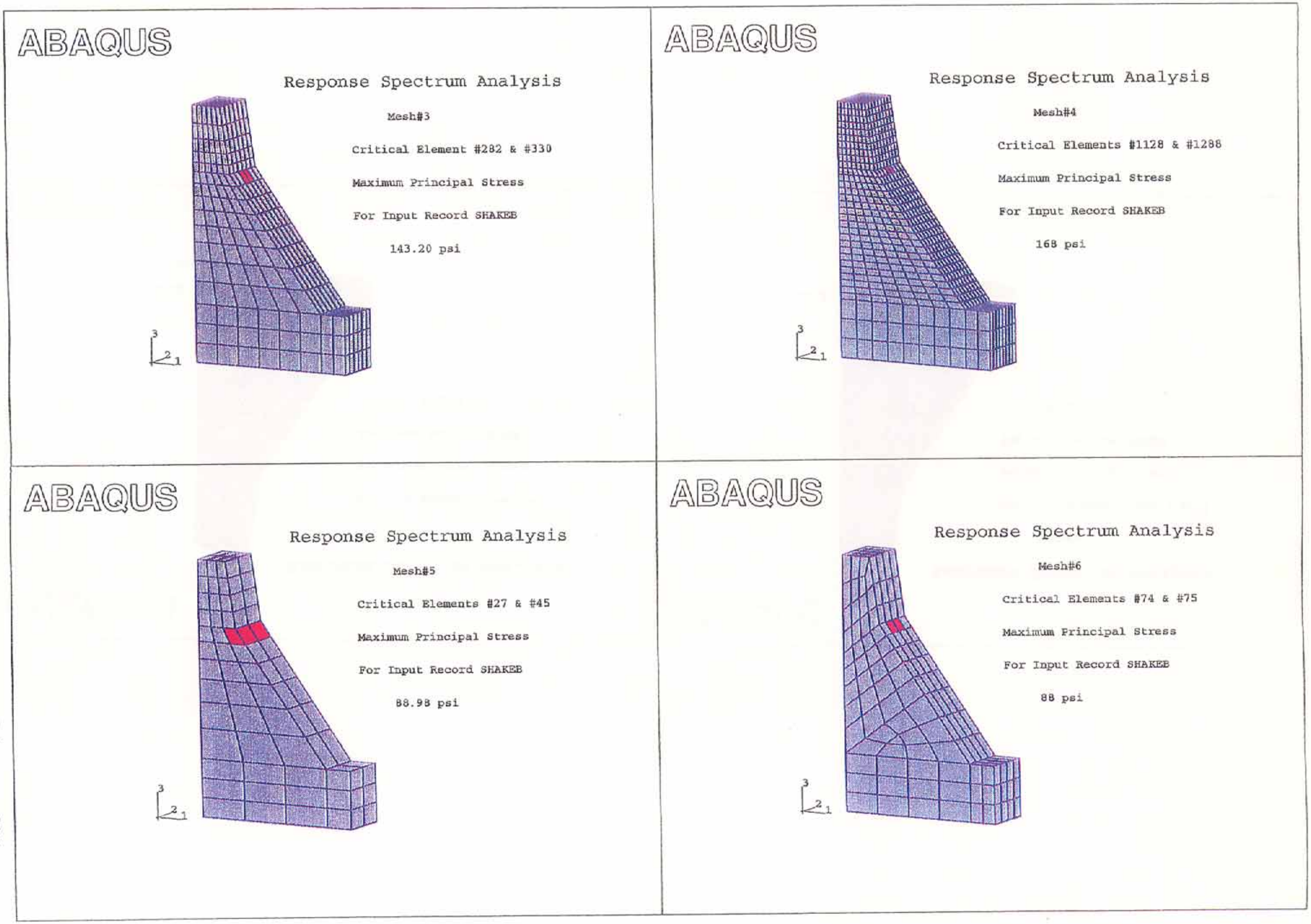

ABAQUS
Response Spectrum Analysis
Mesh#1
Critical Element #1366,1369
Maximum Principal Stress
For Input Record SHAKEB
227.60 psi
ABAQUS
Response Spectrum Analysis
Mesh#2
Critical Elements #120 & #123
Maximum Principal Stress
For Input Record SHAKEB
149 psi

Figure f9



ABAQUS
Response Spectrum Analysis
Mesh#3
Critical Element #282 & #330
Maximum Principal Stress
For Input Record SHAKEB
143.20 psi
ABAQUS
Response Spectrum Analysis
Mesh#4
Critical Elements #1128 & #1288
Maximum Principal Stress
For Input Record SHAKEB
168 psi
ABAQUS
Response Spectrum Analysis
Mesh#5
Critical Elements #27 & #45
Maximum Principal Stress
For Input Record SHAKEB
88.98 psi
ABAQUS
Response Spectrum Analysis
Mesh#6
Critical Elements #74 & #75
Maximum Principal Stress
For Input Record SHAKEB
88 psi

Figure f10

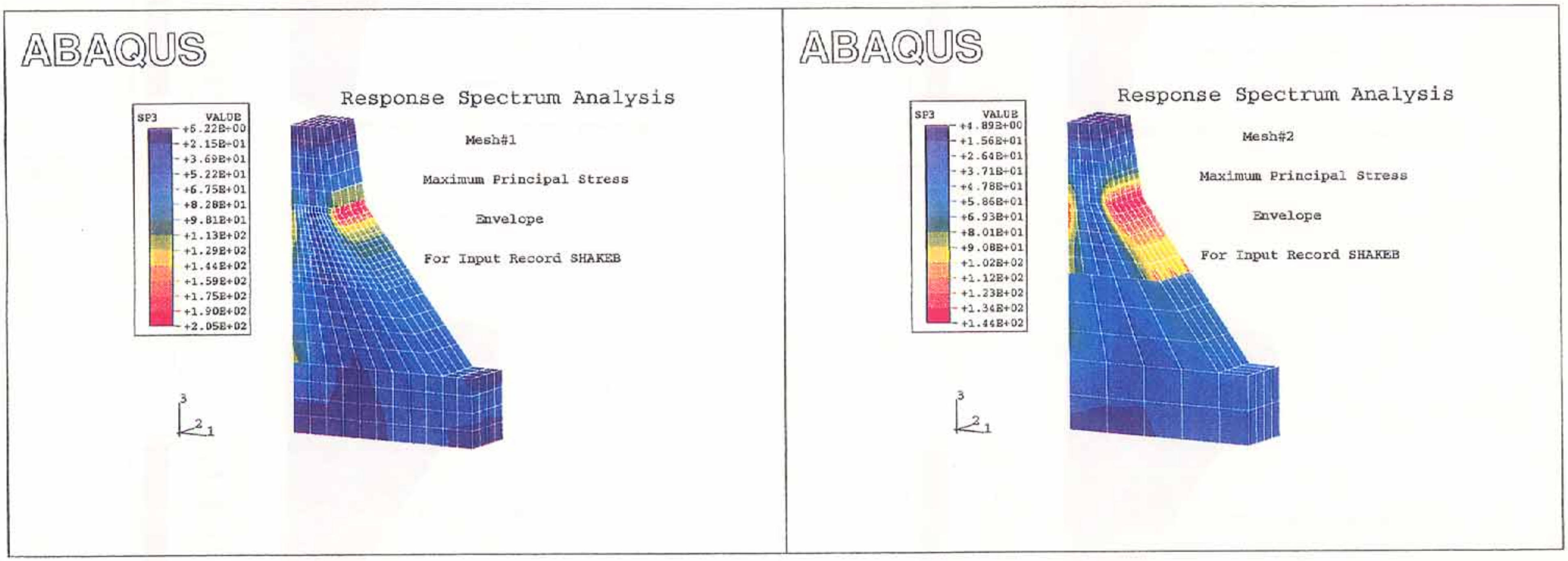
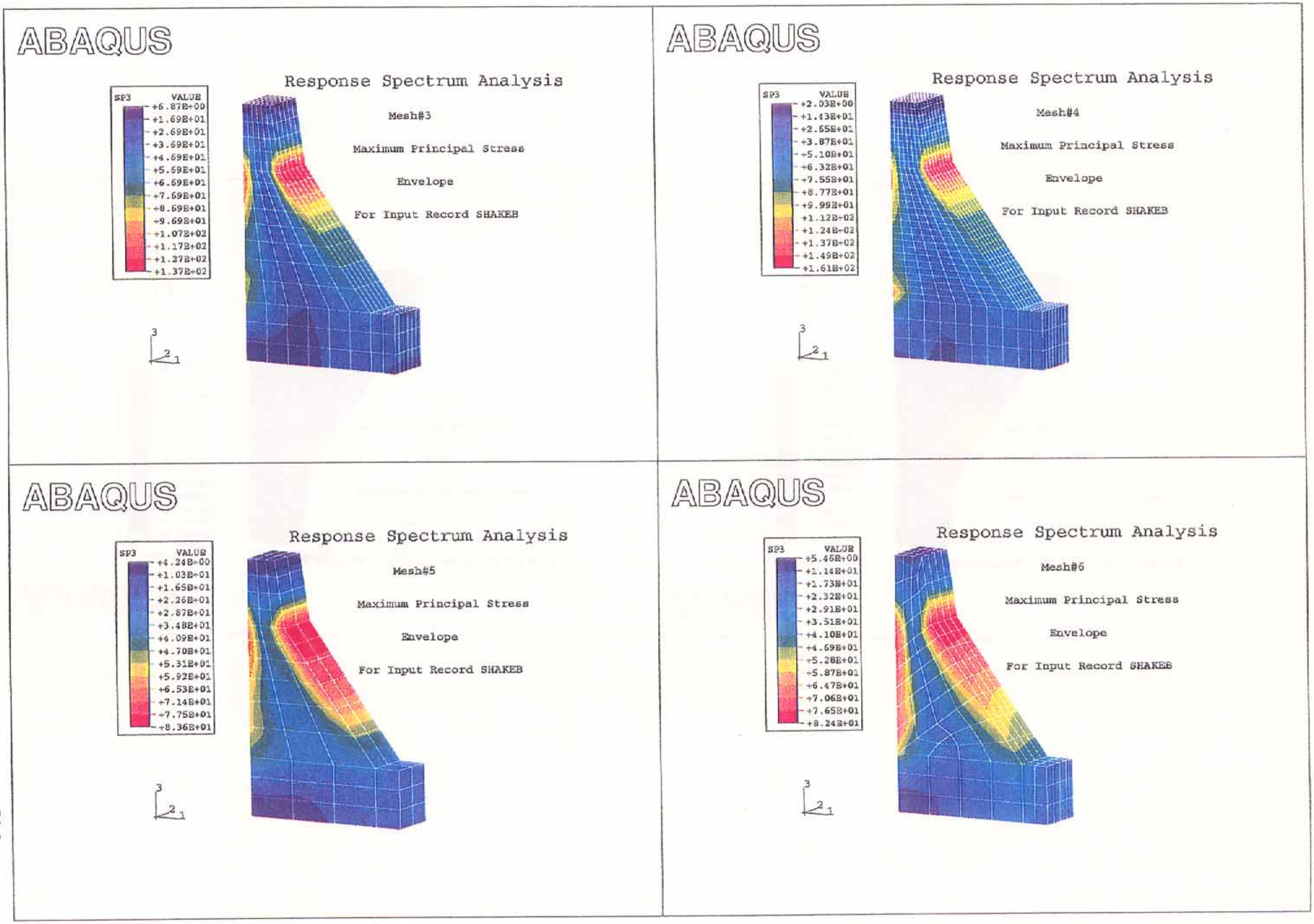

ABAQUS
Response Spectrum Analysis
Mesh#1
Maximum Principal Stress
Envelope
For Input Record SHAKEB
SP3 VALUE
+6.22E+00
+2.15E+01
+3.69E+01
+5.22E+01
+6.75E+01
+8.28E+01
+9.81E+01
+1.13E+02
+1.29E+02
+1.44E+02
+1.59E+02
+1.75E+02
+1.90E+02
+2.05E+02
3
2
1
ABAQUS
Response Spectrum Analysis
Mesh#2
Maximum Principal Stress
Envelope
For Input Record SHAKEB
SP3 VALUE
+4.89E+00
+1.56E+01
+2.64E+01
+3.71E+01
+4.78E+01
+5.86E+01
+6.93E+01
+8.01E+01
+9.08E+01
+1.02E+02
+1.12E+02
+1.23E+02
+1.34E+02
+1.44E+02
3
2
1

Figure f11



ABAQUS
Response Spectrum Analysis
Mesh#3
Maximum Principal Stress
Envelope
For Input Record SHAKEB
SP3 VALUE
+6.87E+00
+1.69E+01
+2.69E+01
+3.69E+01
+4.69E+01
+5.69E+01
+6.69E+01
+7.69E+01
+8.69E+01
+9.69E+01
+1.07E+02
+1.17E+02
+1.27E+02
+1.37E+02
3
2
1
ABAQUS
Response Spectrum Analysis
Mesh#4
Maximum Principal Stress
Envelope
For Input Record SHAKEB
SP3 VALUE
+2.03E+00
+1.43E+01
+2.65E+01
+3.87E+01
+5.10E+01
+6.32E+01
+7.55E+01
+8.77E+01
+9.99E+01
+1.12E+02
+1.24E+02
+1.37E+02
+1.49E+02
+1.61E+02
3
2
1
ABAQUS
Response Spectrum Analysis
Mesh#5
Maximum Principal Stress
Envelope
For Input Record SHAKEB
SP3 VALUE
+4.24E+00
+1.03E+01
+1.65E+01
+2.26E+01
+2.87E+01
+3.48E+01
+4.09E+01
+4.70E+01
+5.31E+01
+5.92E+01
+6.53E+01
+7.14E+01
+7.75E+01
+8.36E+01
3
2
1
ABAQUS
Response Spectrum Analysis
Mesh#6
Maximum Principal Stress
Envelope
For Input Record SHAKEB
SP3 VALUE
+5.46E+00
+1.14E+01
+1.73E+01
+2.32E+01
+2.91E+01
+3.51E+01
+4.10E+01
+4.69E+01
+5.28E+01
+5.87E+01
+6.47E+01
+7.06E+01
+7.65E+01
+8.24E+01
3
2
1

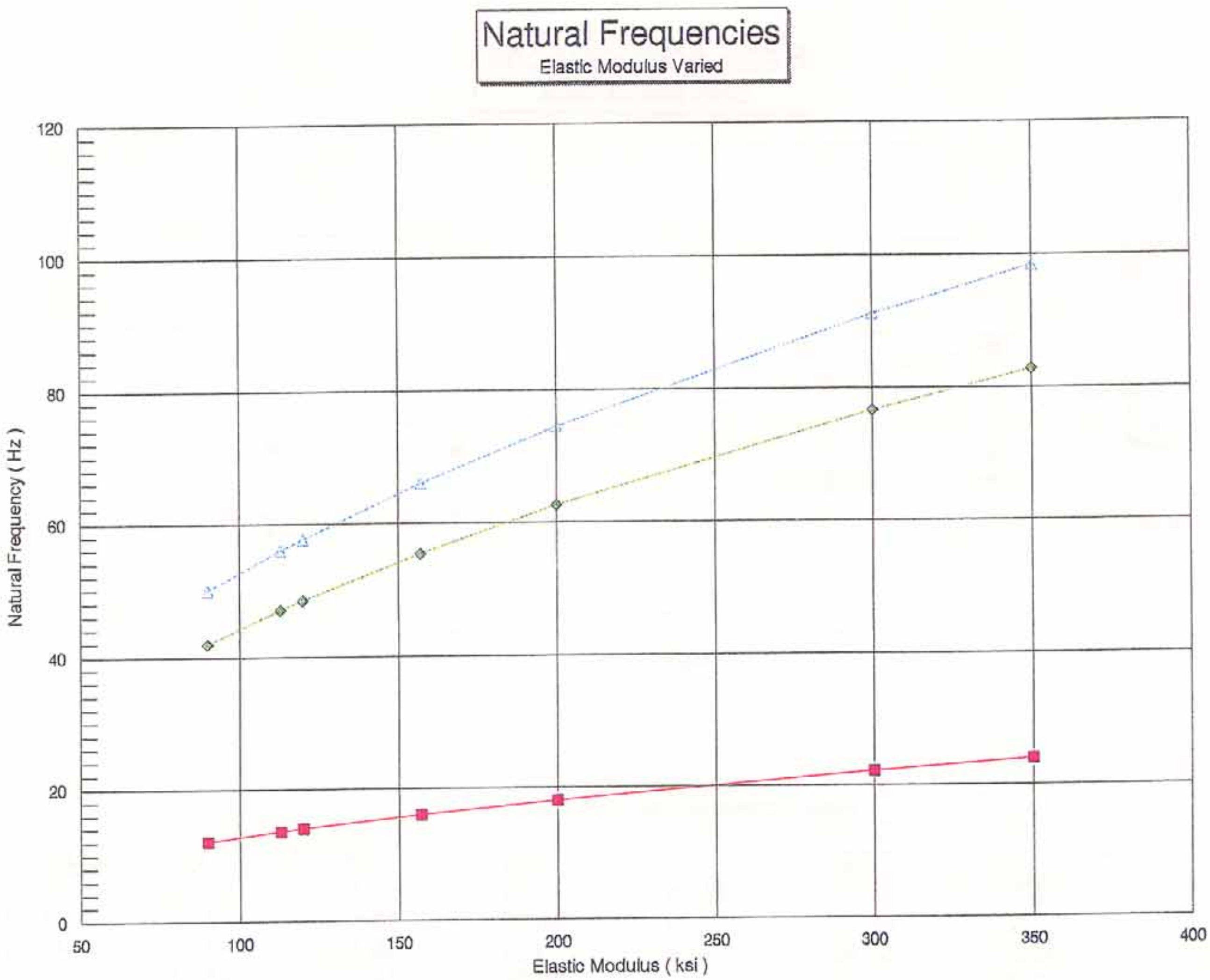
Figure f12

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3

Material Properties

E = (90, 113, 120, 157, 200, 300, 350 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Natural Frequencies (Hz)								
Mode	90	113	120	157	200	300	350	LAB
1	12.1	13.6	14.0	16.0	18.0	22.2	23.9	18.0
2	23.2	26.0	26.8	30.6	34.6	42.4	45.7	24.0
3	41.9	47.0	48.4	55.4	62.5	76.6	82.7	30.0
4	49.9	55.9	57.6	65.9	74.4	91.1	98.4	
5	52.1	58.4	60.2	68.8	77.7	95.2	102.8	
6	53.8	60.2	62.1	71.0	80.1	98.1	106.0	
7	57.1	64.0	65.9	75.4	85.1	104.2	112.6	
8	57.8	64.8	66.8	76.4	86.2	105.6	114.0	
9	58.4	65.4	67.4	77.1	87.0	106.6	115.1	
10	59.5	66.7	68.7	78.6	88.7	108.7	117.4	

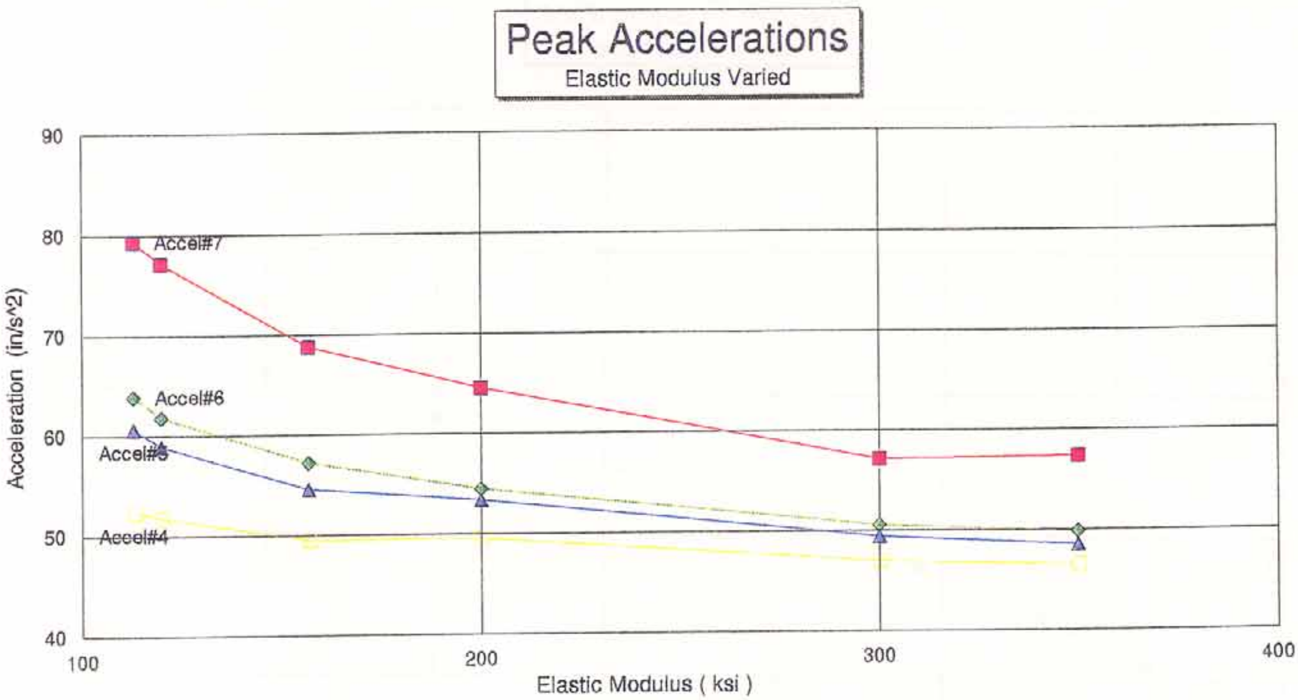
Figure g1

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3

Material Properties

E = (113, 120, 157, 200, 300, 350 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

	113	120	157	200	300	350	LAB
Accel#7	79.31	77.11	68.75	64.53	57.14	57.39	53.26
Accel#6	63.80	61.74	57.19	54.46	50.50	49.85	51.72
Accel#5	60.60	58.90	54.54	53.34	49.42	48.51	49.26
Accel#4	52.28	51.69	49.47	49.50	46.97	46.47	47.72

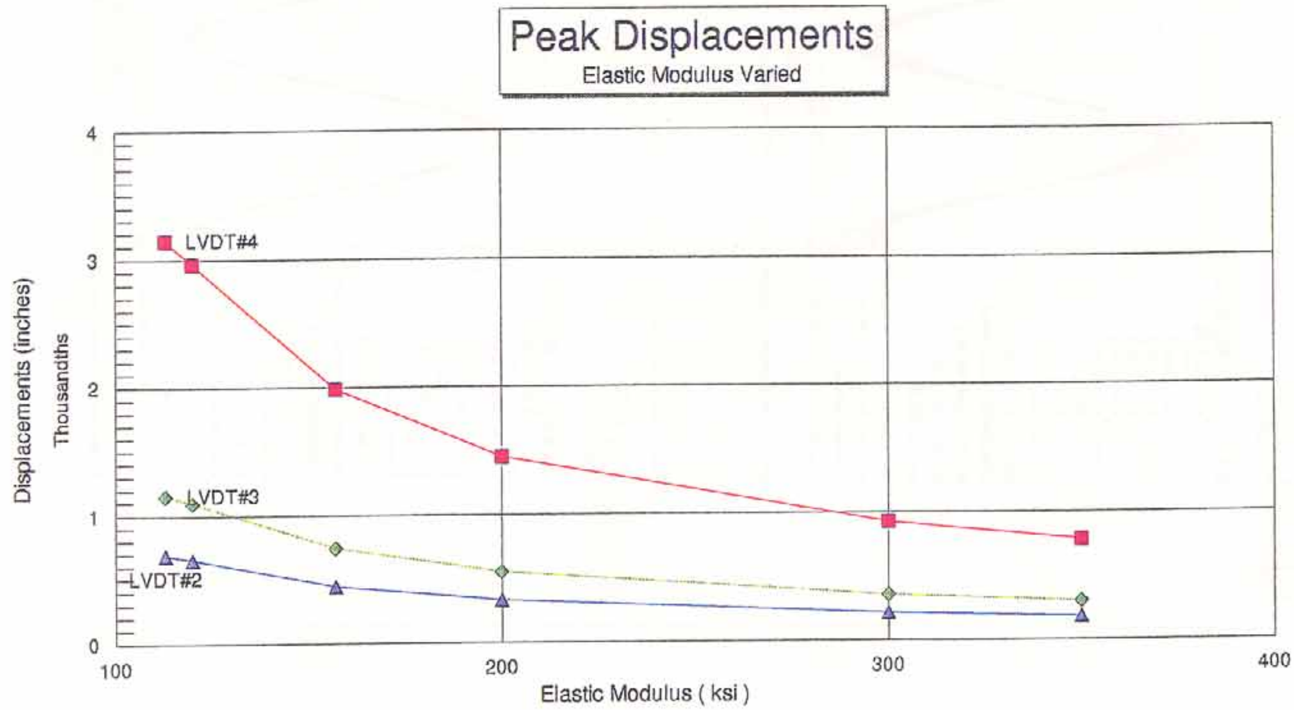
Figure g2

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3

Material Properties

E = (113, 120, 157, 200, 300, 350 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (inches)							
	113	120	157	200	300	350	LAB
LVDT#4	3.1E-03	3.0E-03	2.0E-03	1.5E-03	9.2E-04	7.8E-04	7.2E-04
LVDT#3	1.2E-03	1.1E-03	7.4E-04	5.5E-04	3.6E-04	3.0E-04	3.1E-04
LVDT#2	6.9E-04	6.5E-04	4.4E-04	3.3E-04	2.2E-04	1.8E-04	2.1E-04

Figure g3

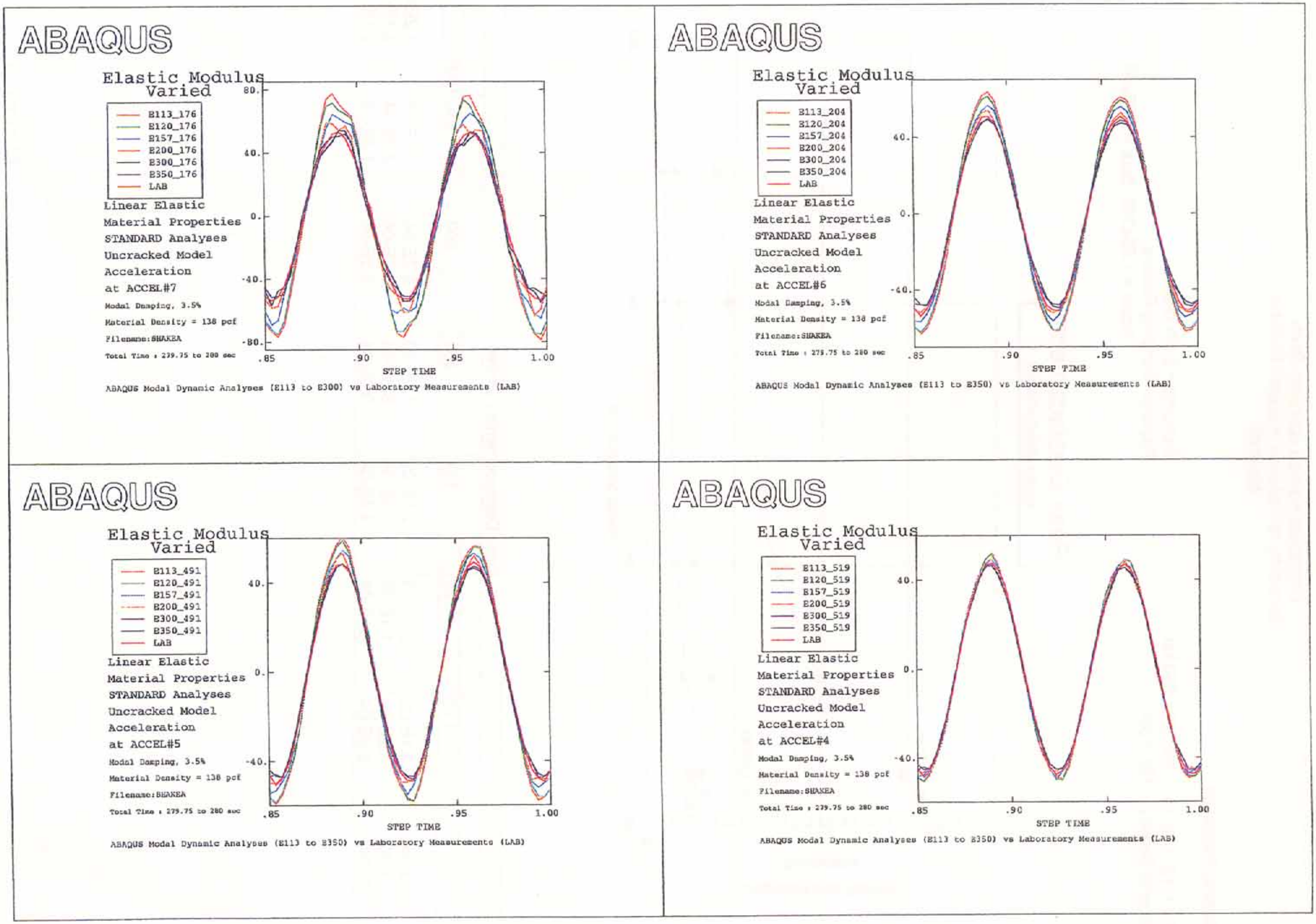

ABAQUS
Elastic Modulus Varied
E113_176
E120_176
E157_176
E200_176
E300_176
E350_176
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Modal Damping, 3.5%
Material Density = 138 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses (E113 to E300) vs Laboratory Measurements (LAB)
ABAQUS
Elastic Modulus Varied
E113_204
E120_204
E157_204
E200_204
E300_204
E350_204
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Modal Damping, 3.5%
Material Density = 138 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses (E113 to E350) vs Laboratory Measurements (LAB)
ABAQUS
Elastic Modulus Varied
E113_491
E120_491
E157_491
E200_491
E300_491
E350_491
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Modal Damping, 3.5%
Material Density = 138 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses (E113 to E350) vs Laboratory Measurements (LAB)
ABAQUS
Elastic Modulus Varied
E113_519
E120_519
E157_519
E200_519
E300_519
E350_519
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Modal Damping, 3.5%
Material Density = 138 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses (E113 to E350) vs Laboratory Measurements (LAB)

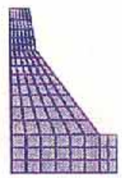
Figure 94

ABAQUS

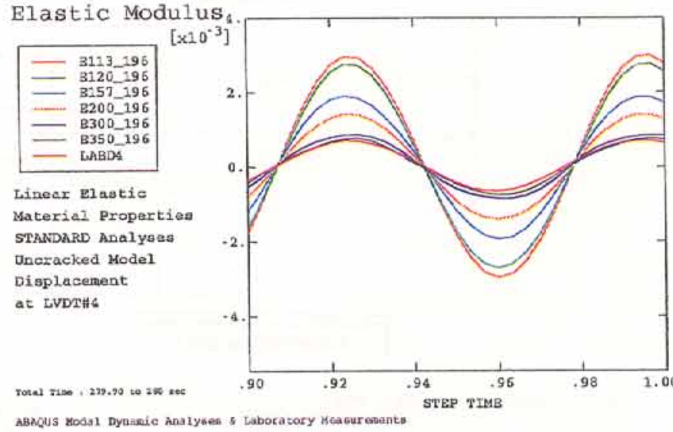
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus

Comparison of Displacements
ABAQUS STANDARD
Modal Dynamic Analysis

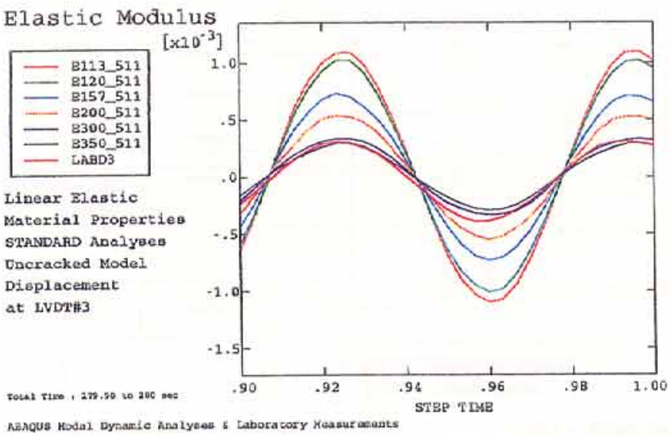
Input Record SHAKEA
Modal Damping, 3.5%
Density = 138.2 pcf
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

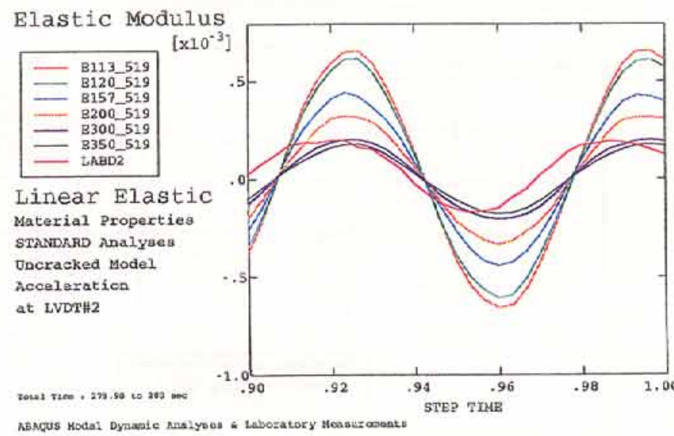


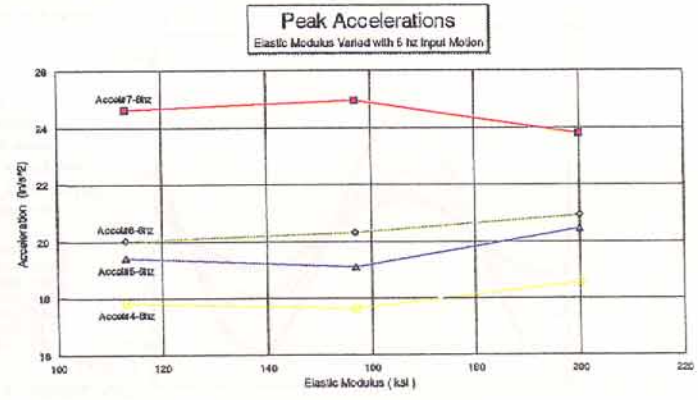
Figure 95

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
6 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

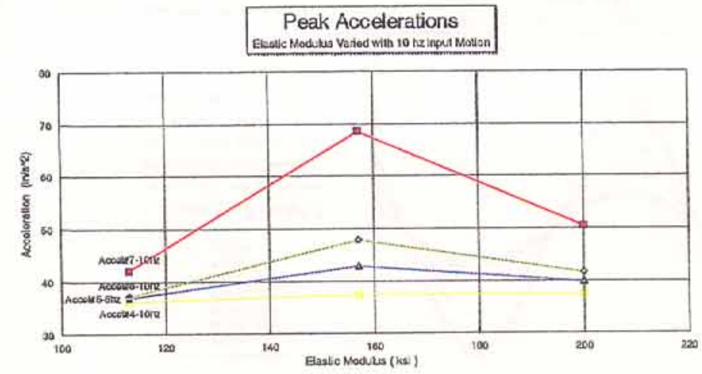
10 hz Input	Motion	113	157	200	Lab	10 hz
	Accel#7-6hz	24.62	24.96	23.79	Accel#7-6hz	17.55
	Accel#6-6hz	20.02	20.31	20.93	Accel#6-6hz	17.86
	Accel#5-6hz	19.40	19.09	20.45	Accel#5-6hz	16.93
	Accel#4-6hz	17.84	17.65	18.56	Accel#4-6hz	17.24

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
10 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

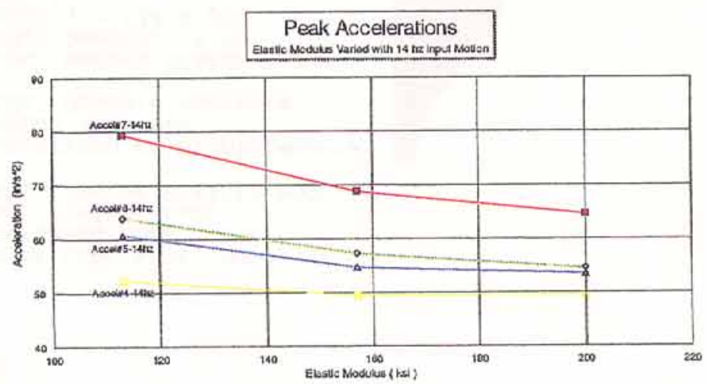
10 hz Input	Motion	113	157	200	Lab	10 hz
	Accel#7-10hz	42.15	68.45	50.39	Accel#7-10hz	37.87
	Accel#6-10hz	37.18	47.84	41.61	Accel#6-10hz	36.94
	Accel#5-10hz	36.79	42.87	39.70	Accel#5-10hz	35.4
	Accel#4-10hz	36.27	37.47	37.50	Accel#4-10hz	36.02

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
14 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

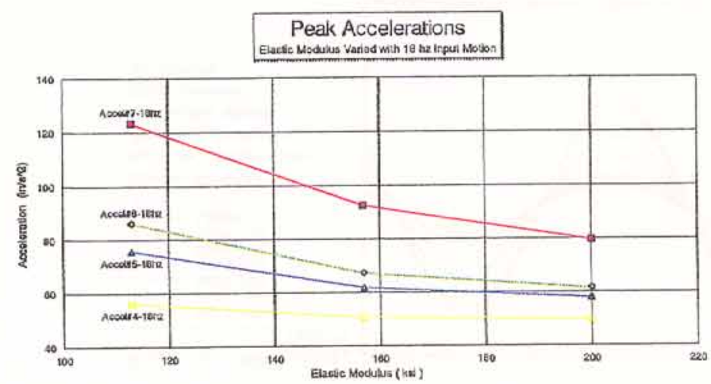
14 hz Input Motion		113	157	200	Lab	14 hz
	Accel#7-14hz	79.31	68.76	64.53	Accel#7-14hz	53.26
	Accel#6-14hz	63.80	57.19	54.46	Accel#6-14hz	50.72
	Accel#5-14hz	60.60	54.54	53.34	Accel#5-14hz	49.26
	Accel#4-14hz	52.28	49.47	49.5	Accel#4-14hz	47.72

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
18 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

18 hz	113	157	200	Lab	18 hz
Accel#7-18hz	123.2	92.43	79.49	Accel#7-18hz	28.94
Accel#6-18hz	85.88	67.23	61.48	Accel#6-18hz	32.62
Accel#5-18hz	75.55	61.65	57.8	Accel#5-18hz	35.71
Accel#4-18hz	56.15	50.82	49.95	Accel#4-18hz	40.02

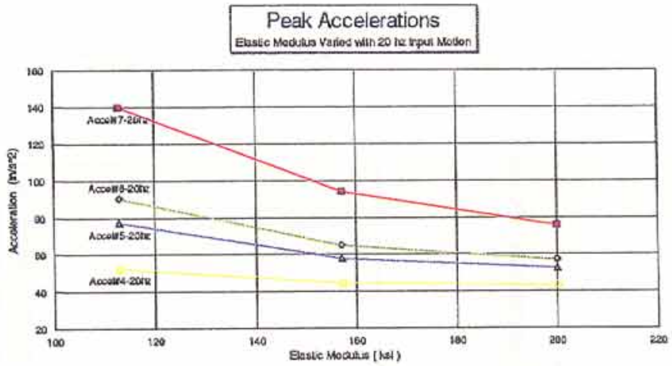
Figure 96

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
20 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

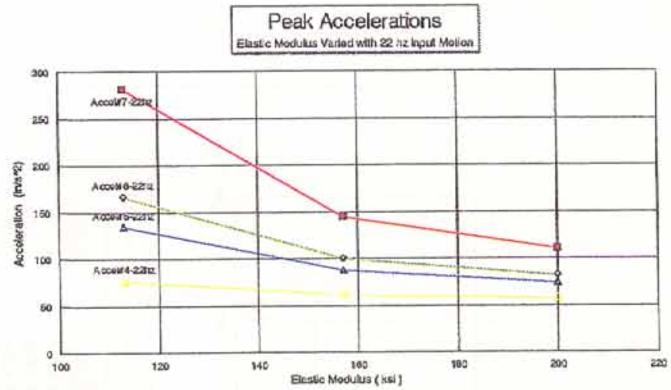
20 hz Input	Motion	113	157	200	Lab	20 hz
	Accel#7-20hz	139.80	94.03	75.55	Accel#7-20hz	65.26
	Accel#6-20hz	90.25	65.09	57.14	Accel#6-20hz	57.57
	Accel#5-20hz	77.07	57.65	52.66	Accel#5-20hz	51.1
	Accel#4-20hz	52.48	44.84	43.31	Accel#4-20hz	44.64

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
22 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

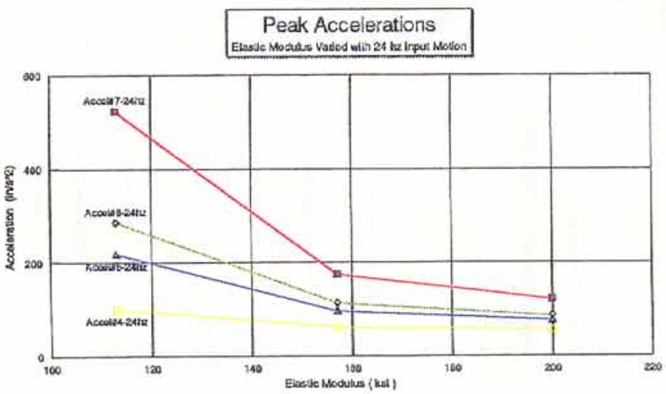
22 hz Input	Motion	113	157	200	Lab	22 hz
	Accel#7-22hz	281.60	144.20	110.20	Accel#7-22hz	65.57
	Accel#6-22hz	166.30	100.10	82.04	Accel#6-22hz	60.03
	Accel#5-22hz	134.40	87.09	73.59	Accel#5-22hz	55.72
	Accel#4-22hz	77.24	61.90	57.66	Accel#4-22hz	52.33

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
24 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

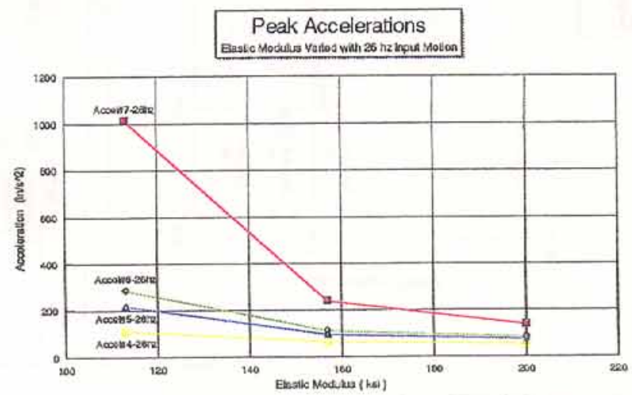
24 hz Input Motion		113	157	200	Lab	24 hz
	Accel#7-24hz	523.00	174.50	121.4	Accel#7-24hz	97.59
	Accel#6-24hz	285.30	112.60	85.59	Accel#6-24hz	79.42
	Accel#5-24hz	217.90	95.42	75.81	Accel#5-24hz	68.96
	Accel#4-24hz	100.50	62.95	56.31	Accel#4-24hz	57.88

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
26 hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

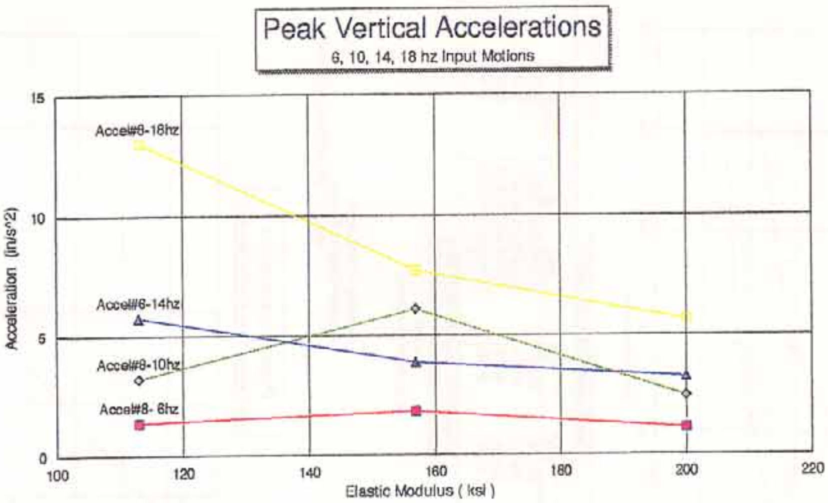
26 hz	113	157	200	Lab	26 hz
Accel#7-26hz	1013	238.6	137.9	Accel#7-26hz	97.59
Accel#6-26hz	285.3	112.6	85.59	Accel#6-26hz	79.42
Accel#5-26hz	217.9	95.42	75.81	Accel#5-26hz	68.96
Accel#4-26hz	111.4	65.02	54.3	Accel#4-26hz	57.88

Figure 97

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
6, 10, 14, 18 hz Input Frequency
Vertical Accelerations

Material Properties
E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



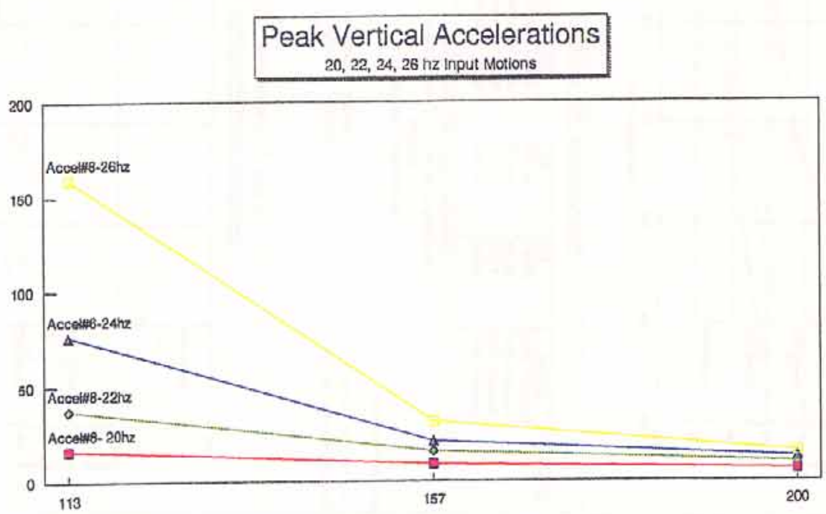
Peak Accelerations (inch / sec ^ 2)

Motion	113	157	200	Lab	
Accel#8- 6hz	1.356	1.791	1.096	Accel#8-6hz	3.694
Accel#8-10hz	3.18	6.07	2.45	Accel#8-10hz	6.773
Accel#6-14hz	5.73	3.87	3.23	Accel#6-14hz	11.08
Accel#8-18hz	12.97	7.66	5.62	Accel#8-18hz	76.96

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
20, 22, 24, 26 hz Input Frequency
Vertical Accelerations

Material Properties
E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

Motion	113	157	200	Lab	
Accel#8- 20hz	16.38	8.679	5.977	Accel#8-6hz	33.86
Accel#8-22hz	37.06	15.86	10.00	Accel#8-10hz	18.47
Accel#6-24hz	76.13	21.01	12.52	Accel#6-14hz	18.78
Accel#8-26hz	158.70	31.27	15.63	Accel#8-18hz	10.78

Figure g8

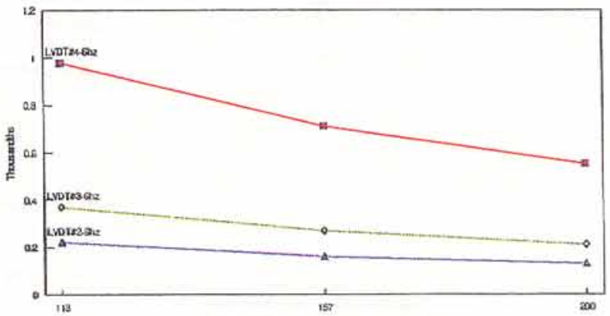
Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
6 Hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248

Peak Displacements
Elastic Modulus Varied using 6 Hz Input Motion



Peak Displacements (Inches)

6 Hz

	113	157	200		LAB
LVDT#4-6hz	9.8E-04	7.1E-04	5.5E-04	LVDT#4-6hz	3.7E-02
LVDT#3-6hz	3.7E-04	2.7E-04	2.1E-04	LVDT#3-6hz	3.7E-02
LVDT#2-6hz	2.2E-04	1.6E-04	1.3E-04	LVDT#2-6hz	3.7E-02

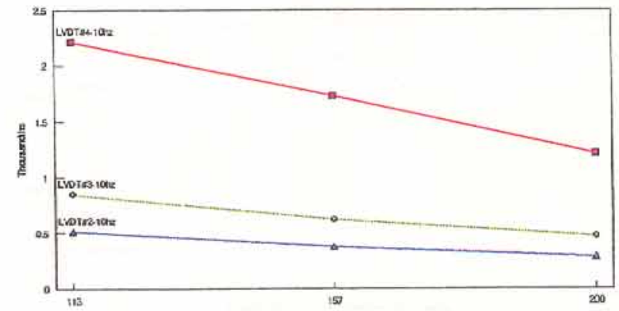
Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
10 Hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248

Peak Displacements
Elastic Modulus Varied using 10 Hz Input Motion



Peak Displacements (Inches)

10 Hz

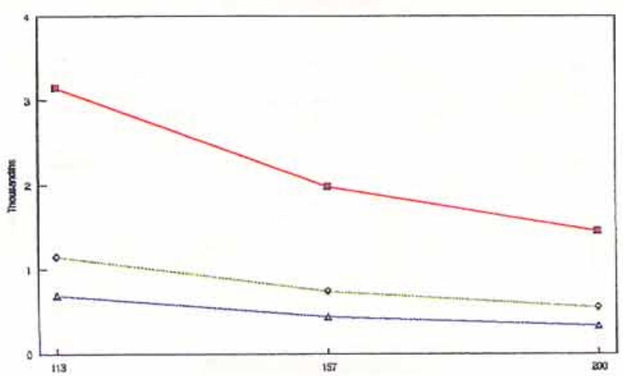
	113	157	200		LAB
LVDT#4-10hz	2.2E-03	1.7E-03	1.2E-03	LVDT#4-10hz	1.3E-03
LVDT#3-10hz	8.4E-04	6.2E-04	4.7E-04	LVDT#3-10hz	6.6E-04
LVDT#2-10hz	5.1E-04	3.7E-04	2.8E-04	LVDT#2-10hz	1.6E-02

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
14 Hz Input Motion

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (Inches)

	113	157	200		LAB
LVDT#4-14hz	3.1E-03	2.0E-03	1.5E-03	LVDT#4-14hz	1.2E-03
LVDT#3-14hz	1.2E-03	7.4E-04	5.5E-04	LVDT#3-14hz	6.2E-04
LVDT#2-14hz	6.9E-04	4.4E-04	3.3E-04	LVDT#2-14hz	1.1E-02

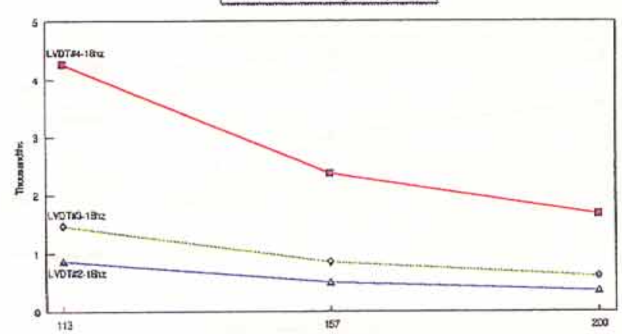
Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
18 Hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248

Peak Displacements
Elastic Modulus Varied using 18 Hz Input Motion



Peak Displacements (Inches)

	113	157	200		LAB
LVDT#4-18hz	4.3E-03	2.4E-03	1.7E-03	LVDT#4-18hz	1.9E-03
LVDT#3-18hz	1.5E-03	8.6E-04	6.2E-04	LVDT#3-18hz	1.2E-03
LVDT#2-18hz	8.7E-04	5.1E-04	3.7E-04	LVDT#2-18hz	6.2E-03

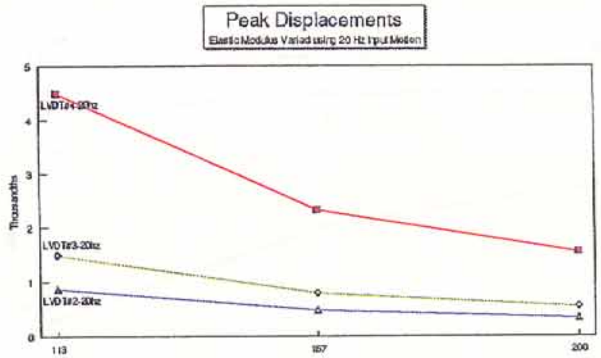
Figure 99

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
20 Hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (Inches)

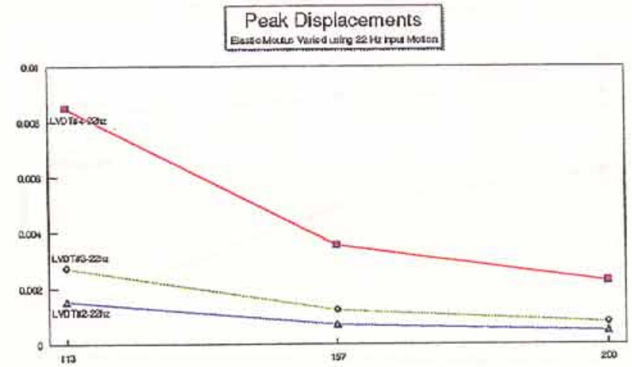
20 Hz		113	157	200		LAB
	LVDT#4-20hz	4.5E-03	2.3E-03	1.6E-03	LVDT#4-20hz	1.7E-03
	LVDT#3-20hz	1.5E-03	8.0E-04	5.5E-04	LVDT#3-20hz	1.2E-03
	LVDT#2-20hz	8.7E-04	4.8E-04	3.4E-04	LVDT#2-20hz	5.5E-03

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
22 Hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (Inches)

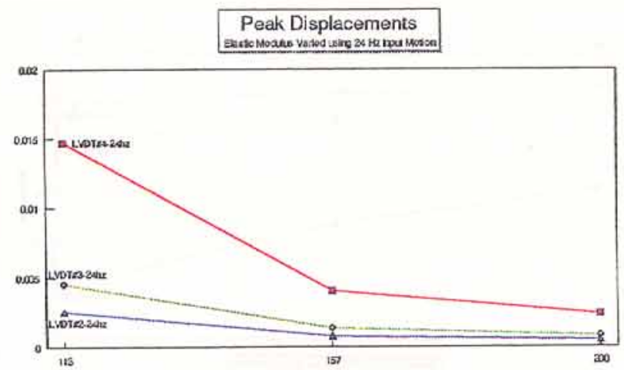
22 Hz		113	157	200		LAB
	LVDT#4-22hz	8.5E-03	3.6E-03	2.3E-03	LVDT#4-22hz	9.7E-04
	LVDT#3-22hz	2.7E-03	1.2E-03	8.1E-04	LVDT#3-22hz	8.1E-04
	LVDT#2-22hz	1.6E-03	7.2E-04	4.7E-04	LVDT#2-22hz	5.6E-03

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
24 Hz Input Motion

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (Inches)

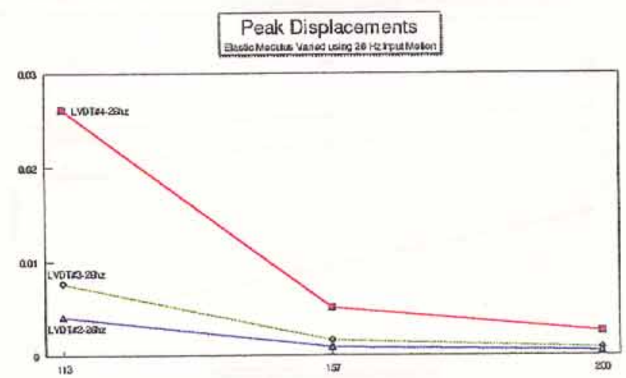
24 Hz		113	157	200		LAB
	LVDT#4-24hz	1.5E-02	4.1E-03	2.4E-03	LVDT#4-24hz	2.0E-03
	LVDT#3-24hz	4.5E-03	1.4E-03	8.4E-04	LVDT#3-24hz	1.1E-03
	LVDT#2-24hz	2.5E-03	7.8E-04	4.9E-04	LVDT#2-24hz	4.8E-03

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Elastic Modulus
Mesh#3
26 Hz Input Frequency

Material Properties

E = (113, 157, 200 ksi)
Material Density = 138.2 pcf

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (Inches)

26 Hz		113	157	200		LAB
	LVDT#4-26hz	2.6E-02	5.1E-03	2.6E-03	LVDT#4-26hz	1.5E-03
	LVDT#3-26hz	7.6E-03	1.6E-03	8.7E-04	LVDT#3-26hz	1.1E-03
	LVDT#2-26hz	4.1E-03	9.3E-04	5.0E-04	LVDT#2-26hz	3.5E-03

Figure 910

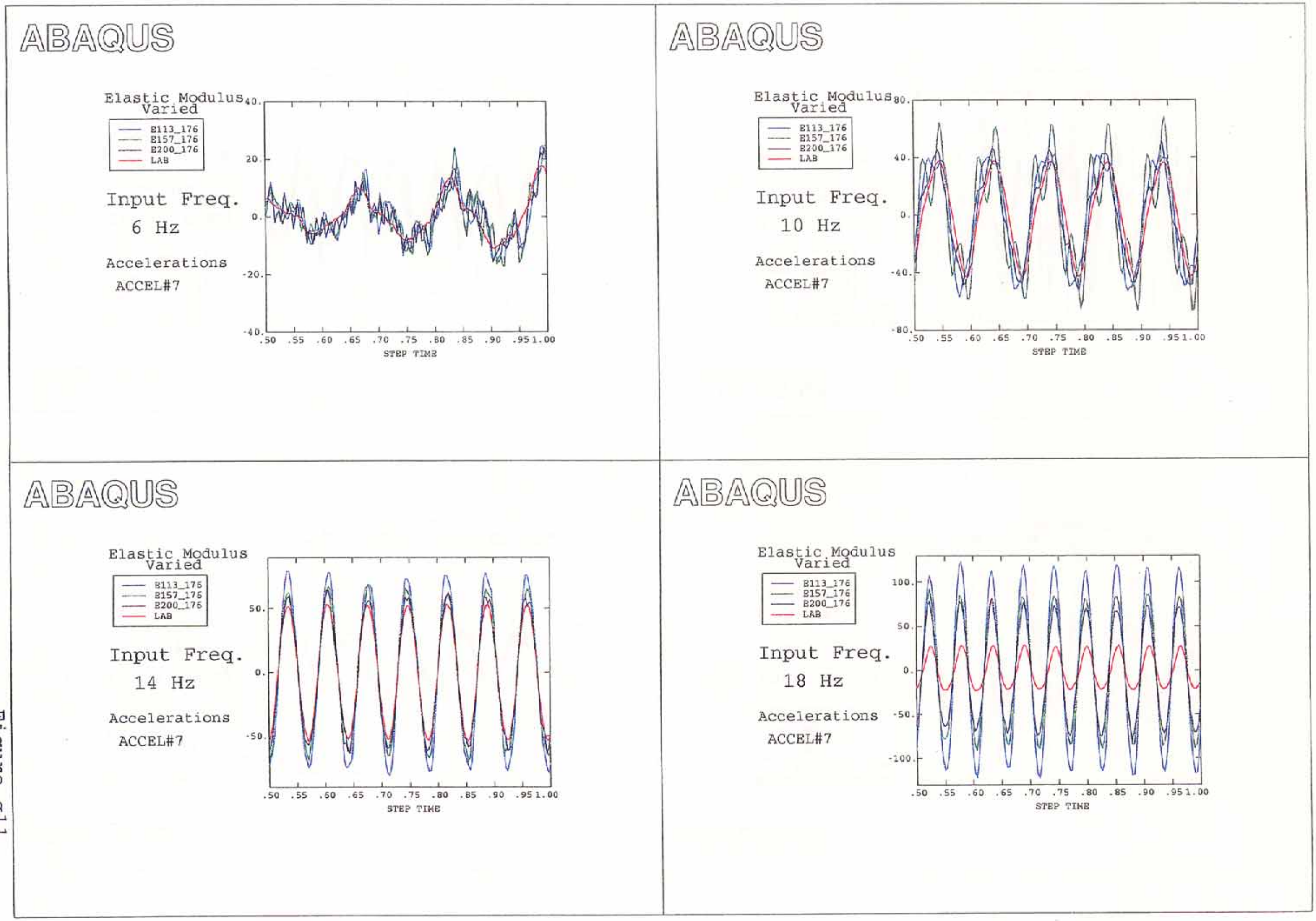

ABAQUS
Elastic Modulus Varied
E113_176
E157_176
E200_176
LAB
Input Freq.
6 Hz
Accelerations
ACCEL#7
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_176
E157_176
E200_176
LAB
Input Freq.
10 Hz
Accelerations
ACCEL#7
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_176
E157_176
E200_176
LAB
Input Freq.
14 Hz
Accelerations
ACCEL#7
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_176
E157_176
E200_176
LAB
Input Freq.
18 Hz
Accelerations
ACCEL#7
STEP TIME

Figure 911

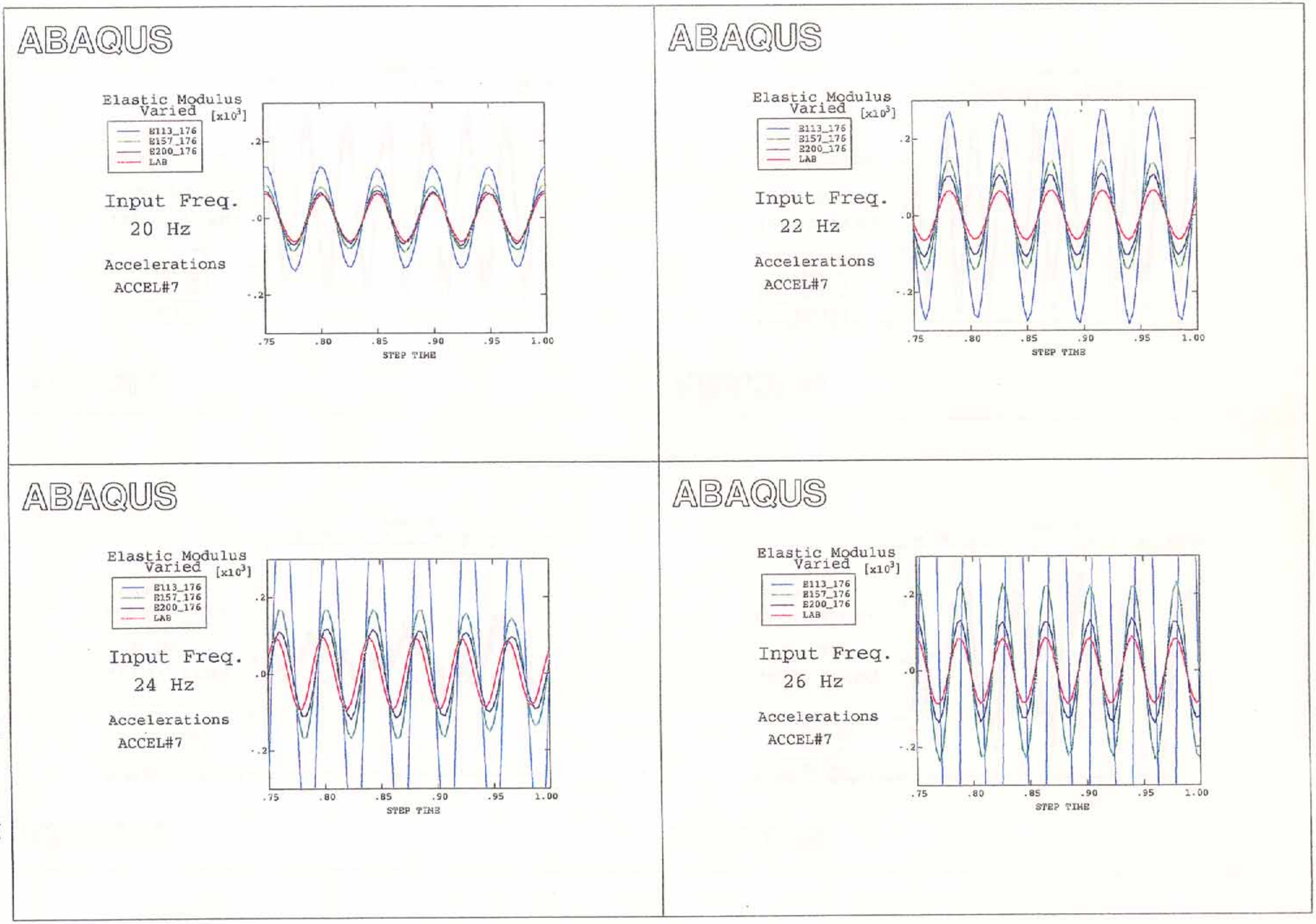
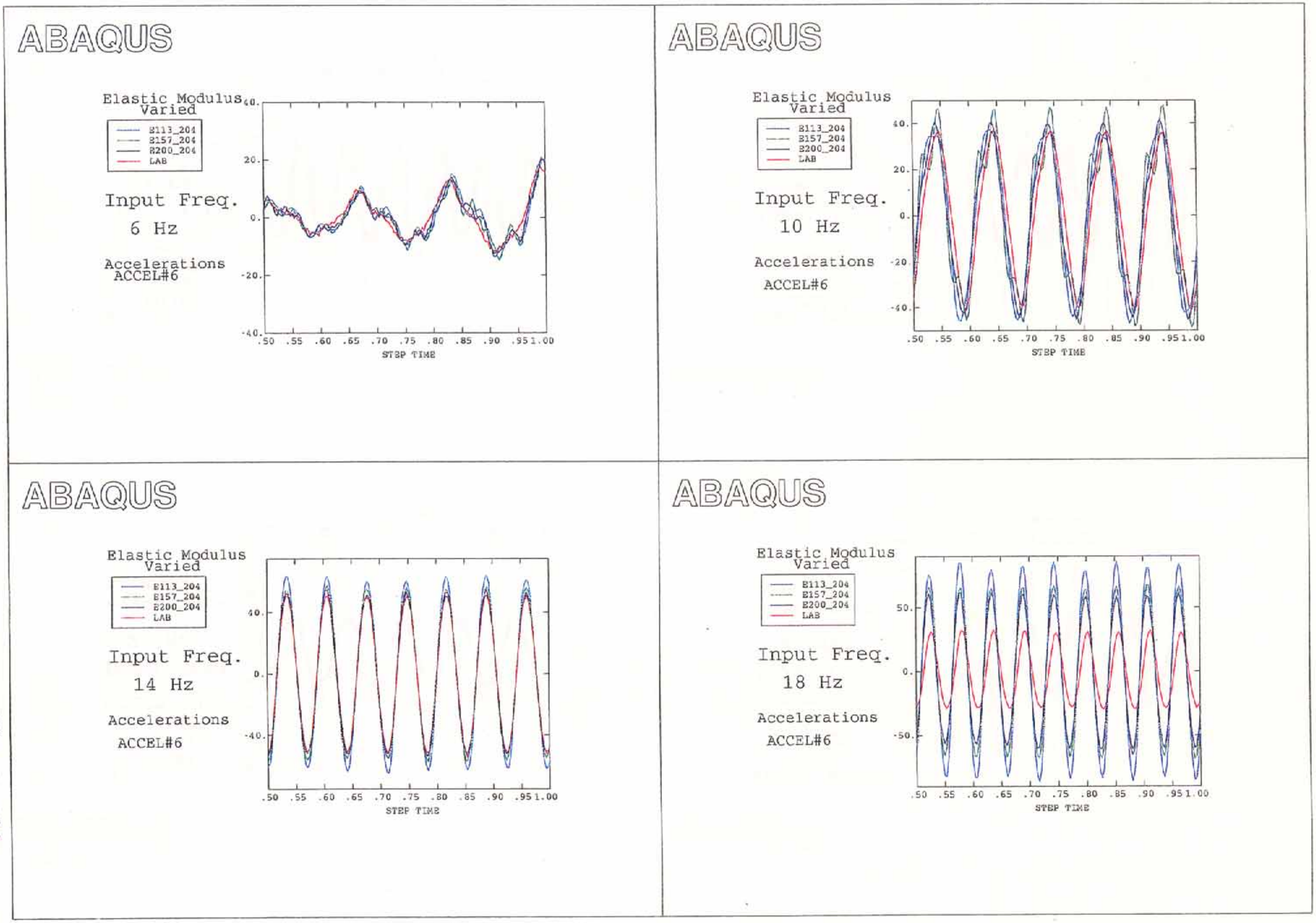

ABAQUS
Elastic Modulus Varied
[x10^3]
E113_176
E157_176
E200_176
LAB
Input Freq.
20 Hz
Accelerations
ACCEL#7
STEP TIME
ABAQUS
Elastic Modulus Varied
Input Freq.
22 Hz
Accelerations
ACCEL#7
ABAQUS
Elastic Modulus Varied
Input Freq.
24 Hz
Accelerations
ACCEL#7
ABAQUS
Elastic Modulus Varied
Input Freq.
26 Hz
Accelerations
ACCEL#7

Figure 912



ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq.
6 Hz
Accelerations
ACCEL#6
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq.
10 Hz
Accelerations
ACCEL#6
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq.
14 Hz
Accelerations
ACCEL#6
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq.
18 Hz
Accelerations
ACCEL#6
STEP TIME

Figure 913

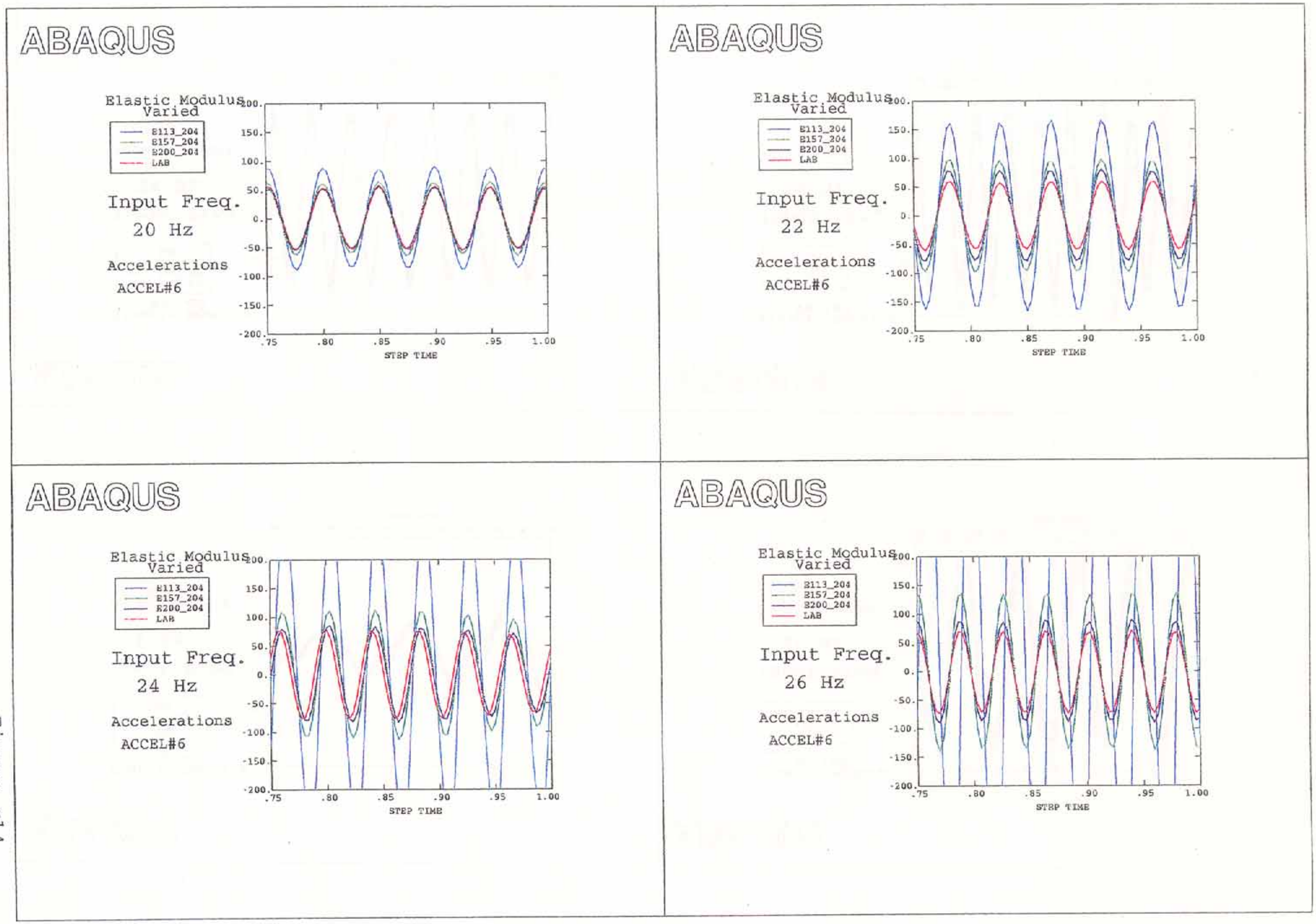

ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq.
20 Hz
Accelerations
ACCEL#6
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq.
22 Hz
Accelerations
ACCEL#6
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq.
24 Hz
Accelerations
ACCEL#6
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_204
E157_204
E200_204
LAB
Input Freq.
26 Hz
Accelerations
ACCEL#6
STEP TIME

Figure g14

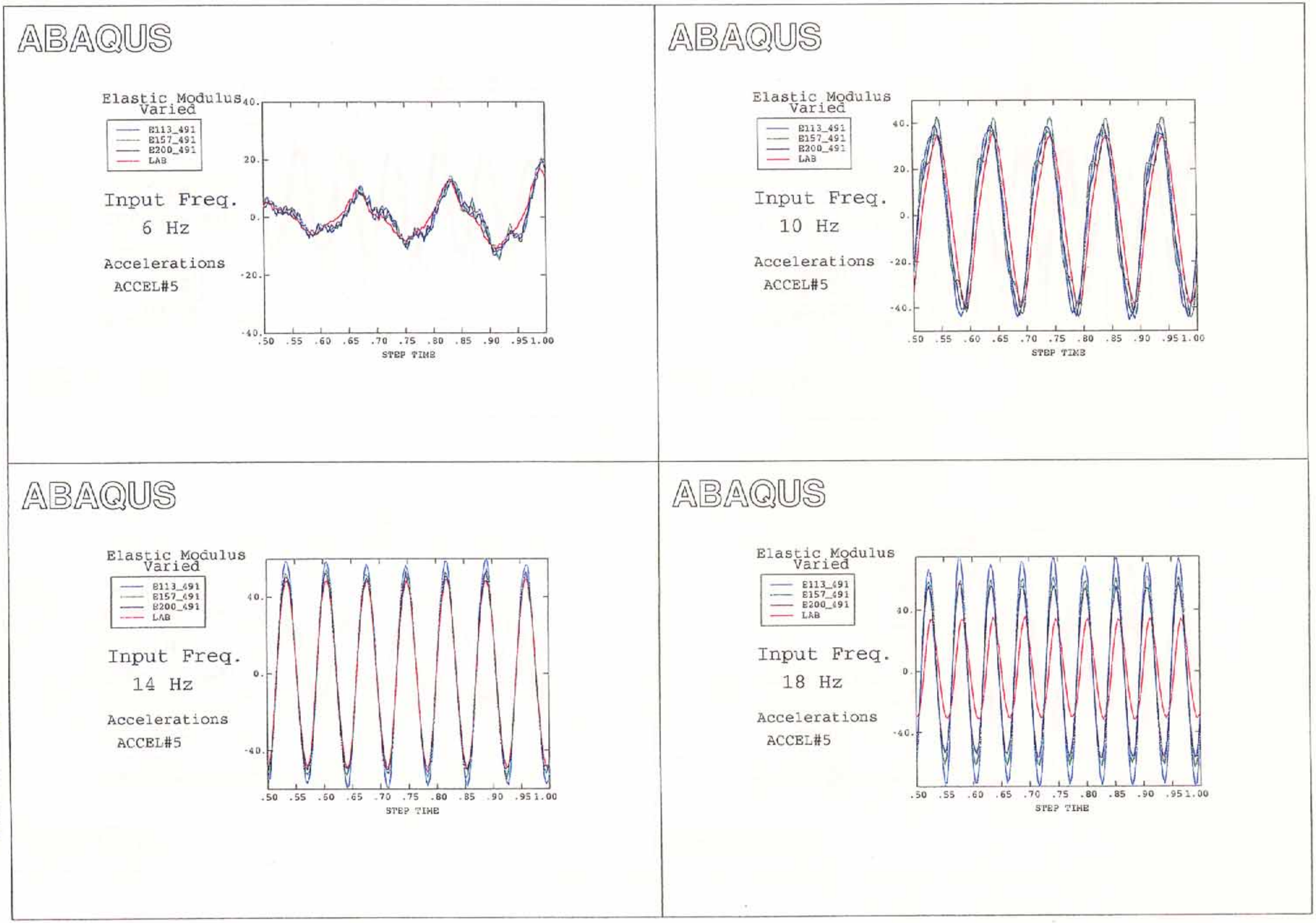
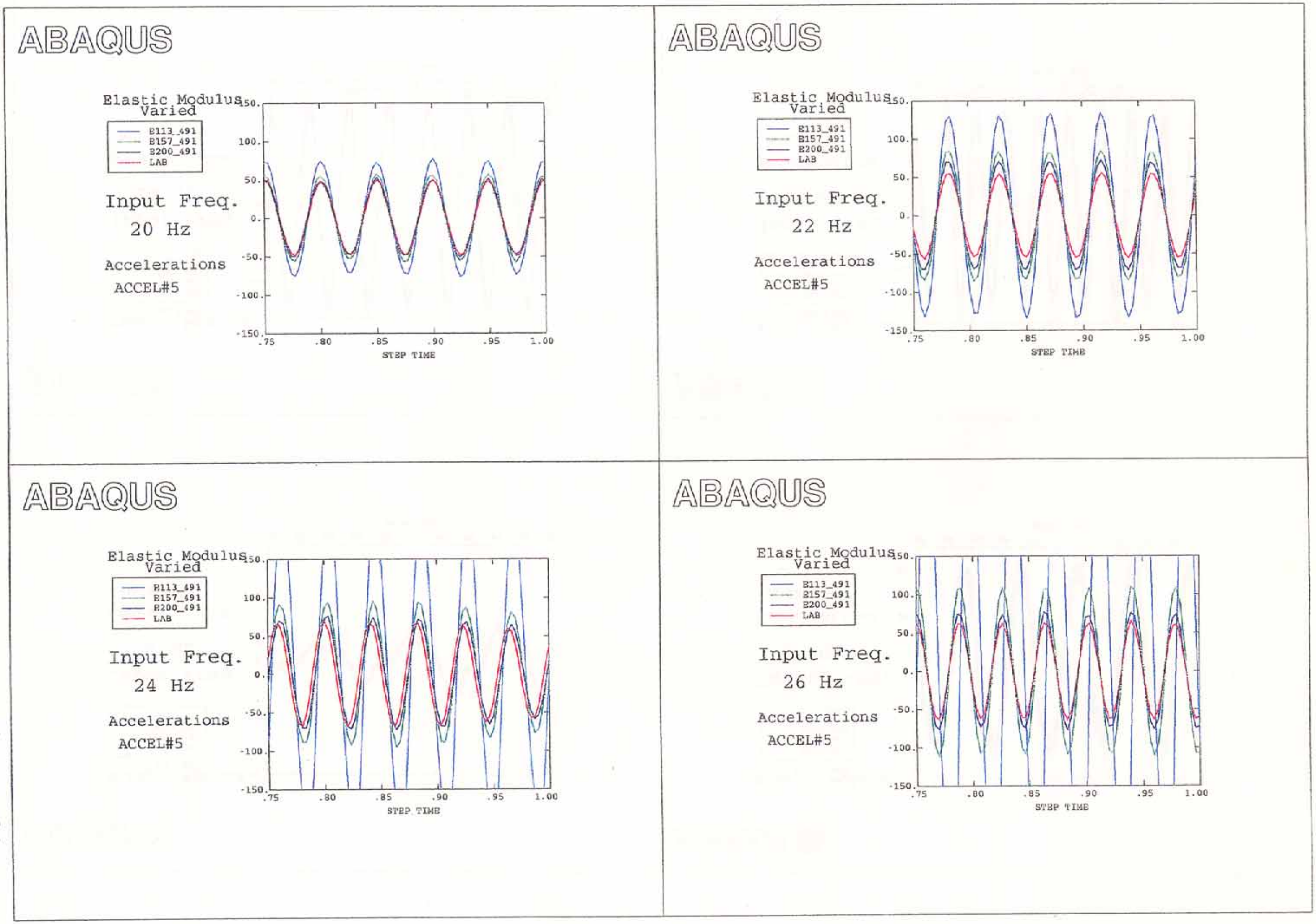

ABAQUS
Elastic Modulus Varied
E113_491
E157_491
E200_491
LAB
Input Freq.
6 Hz
Accelerations
ACCEL#5
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_491
E157_491
E200_491
LAB
Input Freq.
10 Hz
Accelerations
ACCEL#5
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_491
E157_491
E200_491
LAB
Input Freq.
14 Hz
Accelerations
ACCEL#5
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_491
E157_491
E200_491
LAB
Input Freq.
18 Hz
Accelerations
ACCEL#5
STEP TIME

Figure 915



ABAQUS
Elastic Modulus Varied
B113_491
B157_491
B200_491
LAB
Input Freq.
20 Hz
Accelerations
ACCEL#5
STEP TIME
ABAQUS
Elastic Modulus Varied
B113_491
B157_491
B200_491
LAB
Input Freq.
22 Hz
Accelerations
ACCEL#5
STEP TIME
ABAQUS
Elastic Modulus Varied
B113_491
B157_491
B200_491
LAB
Input Freq.
24 Hz
Accelerations
ACCEL#5
STEP TIME
ABAQUS
Elastic Modulus Varied
B113_491
B157_491
B200_491
LAB
Input Freq.
26 Hz
Accelerations
ACCEL#5
STEP TIME

Figure g16

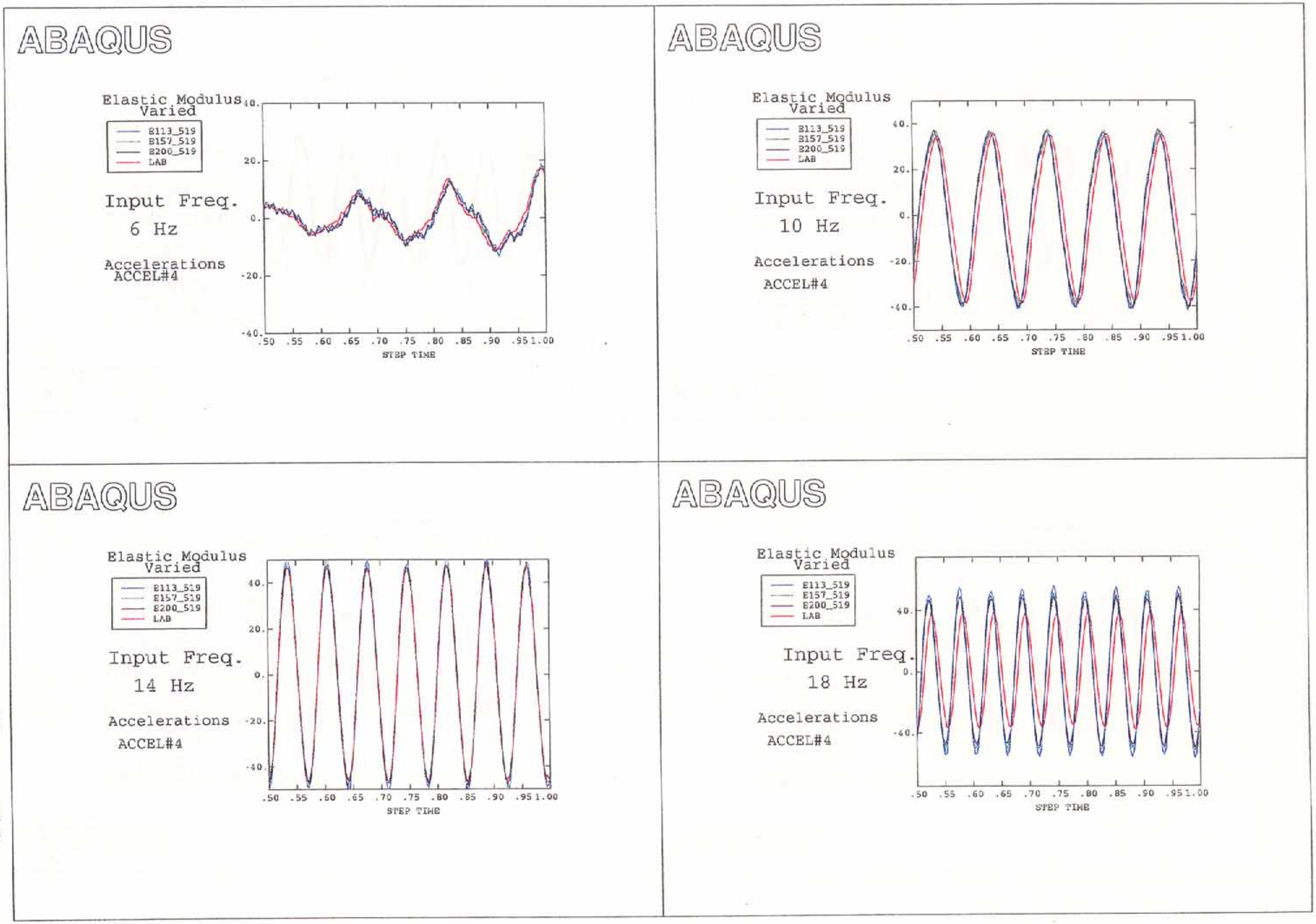

ABAQUS
Elastic Modulus Varied
E113_519
E157_519
E200_519
LAB
Input Freq. 6 Hz
Accelerations ACCEL#4
STEP TIME
ABAQUS
Elastic Modulus Varied
Input Freq. 10 Hz
Accelerations ACCEL#4
ABAQUS
Elastic Modulus Varied
Input Freq. 14 Hz
Accelerations ACCEL#4
ABAQUS
Elastic Modulus Varied
Input Freq. 18 Hz
Accelerations ACCEL#4

Figure 917

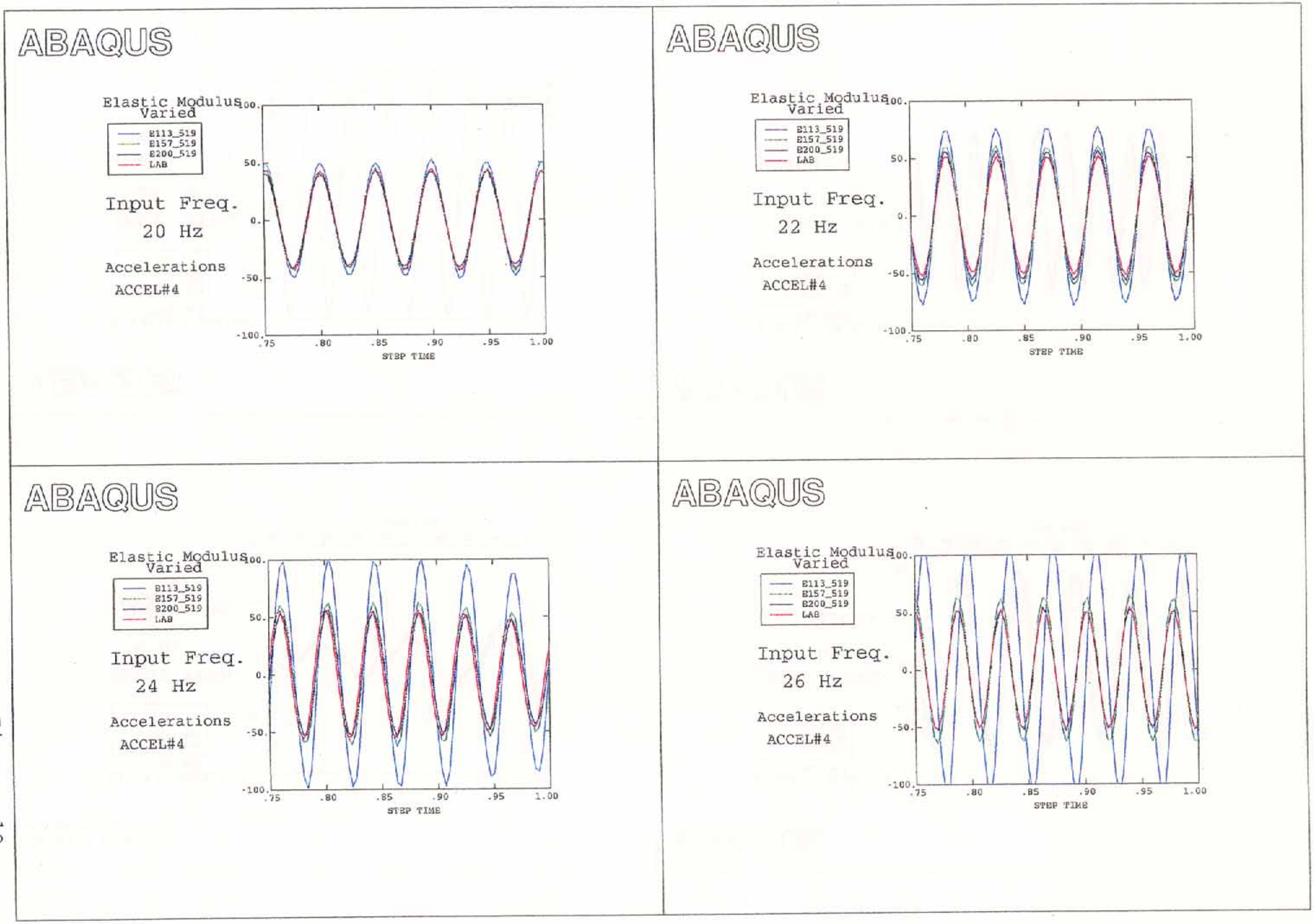

ABAQUS
Elastic Modulus Varied
E113_519
E157_519
E200_519
LAB
Input Freq.
20 Hz
Accelerations
ACCEL#4
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_519
E157_519
E200_519
LAB
Input Freq.
22 Hz
Accelerations
ACCEL#4
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_519
E157_519
E200_519
LAB
Input Freq.
24 Hz
Accelerations
ACCEL#4
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_519
E157_519
E200_519
LAB
Input Freq.
26 Hz
Accelerations
ACCEL#4
STEP TIME

Figure 918

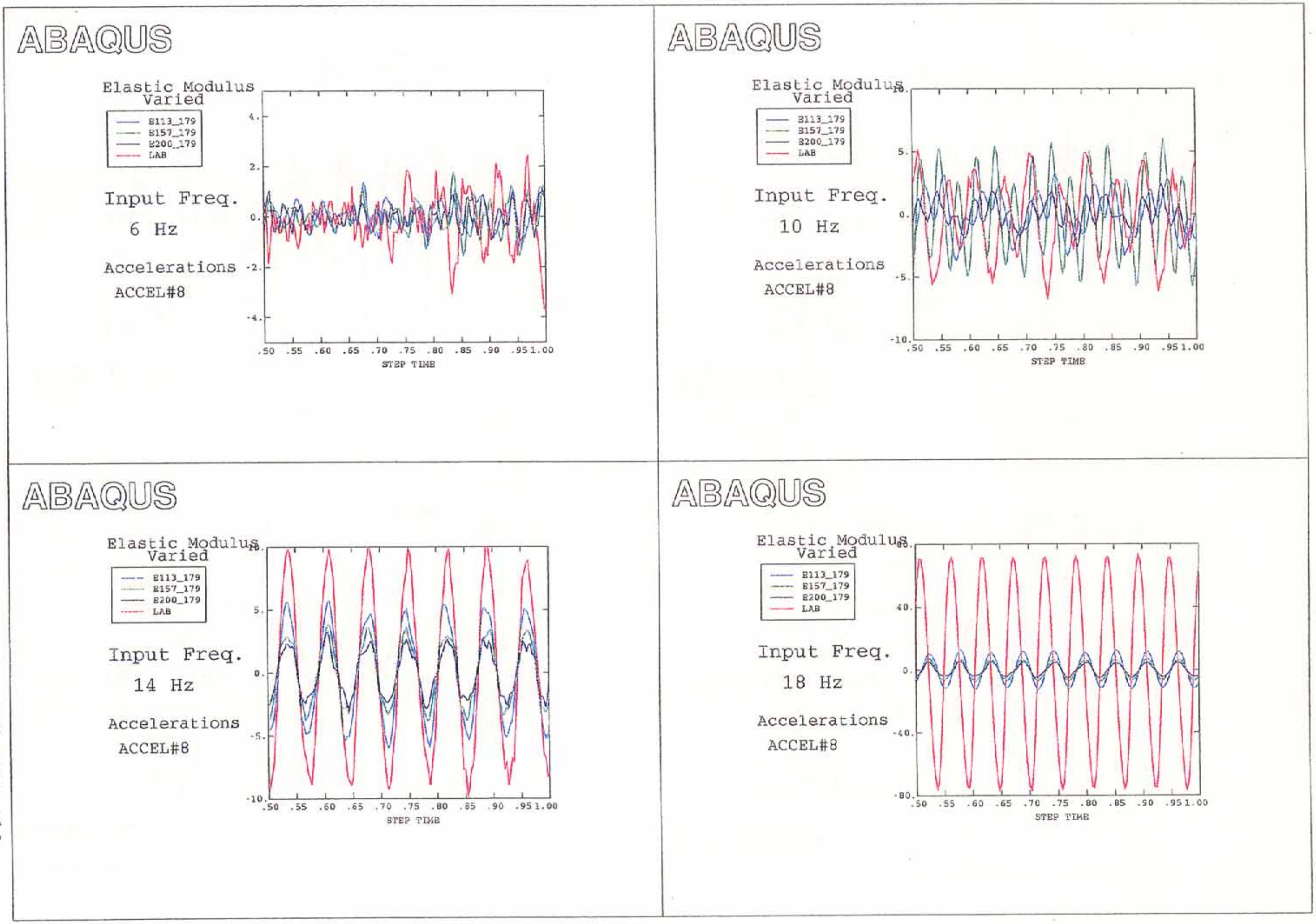

ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq.
6 Hz
Accelerations
ACCEL#8
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq.
10 Hz
Accelerations
ACCEL#8
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq.
14 Hz
Accelerations
ACCEL#8
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq.
18 Hz
Accelerations
ACCEL#8
STEP TIME

Figure 919

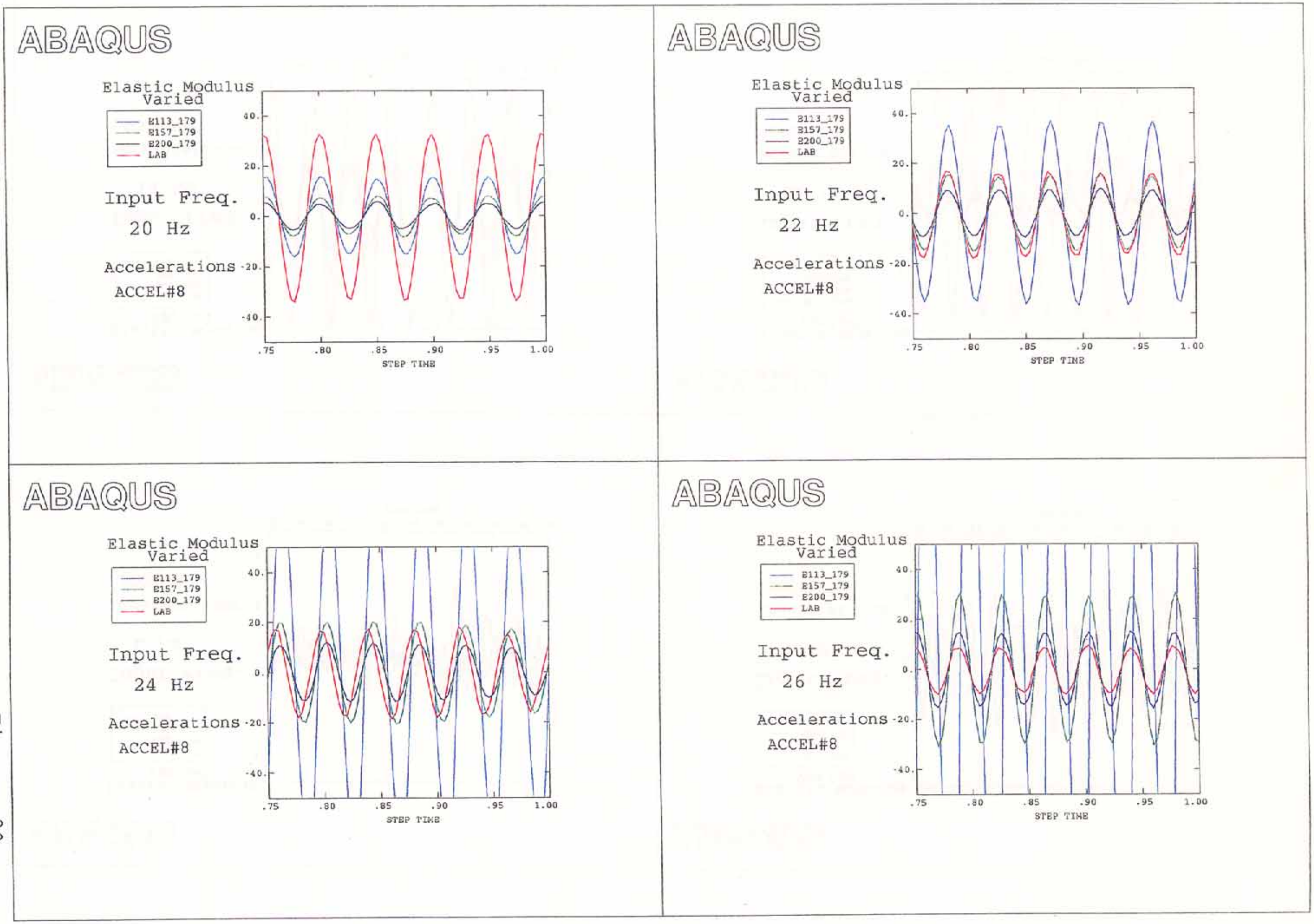

ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq.
20 Hz
Accelerations
ACCEL#8
40.
20.
0.
-20.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq.
22 Hz
Accelerations
ACCEL#8
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq.
24 Hz
Accelerations
ACCEL#8
STEP TIME
ABAQUS
Elastic Modulus Varied
E113_179
E157_179
E200_179
LAB
Input Freq.
26 Hz
Accelerations
ACCEL#8
STEP TIME

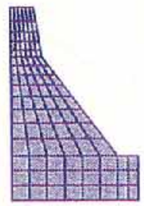
Figure g20

ABAQUS

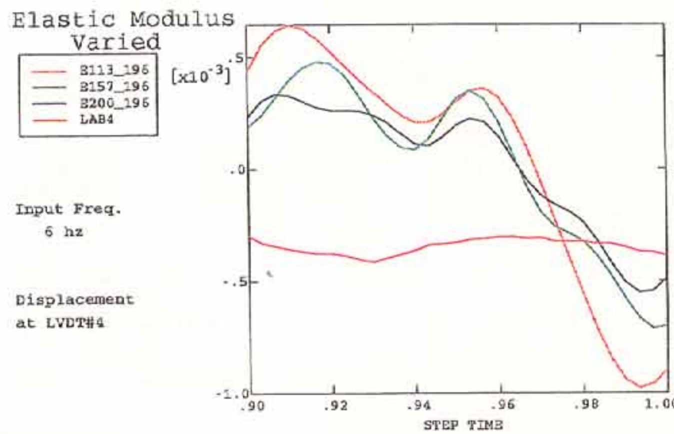
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus

At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis

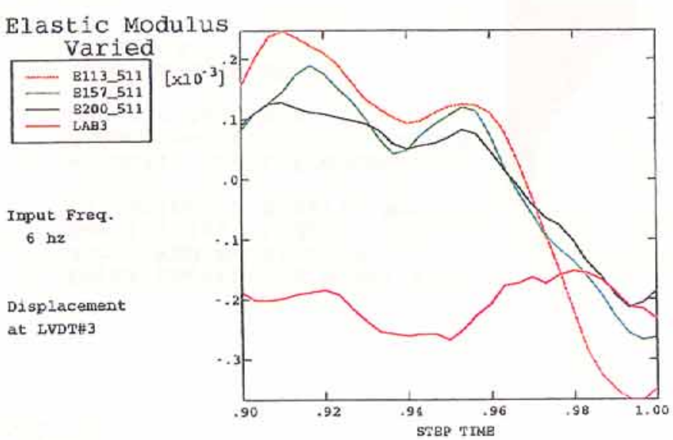
Input Record SHAKEA
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

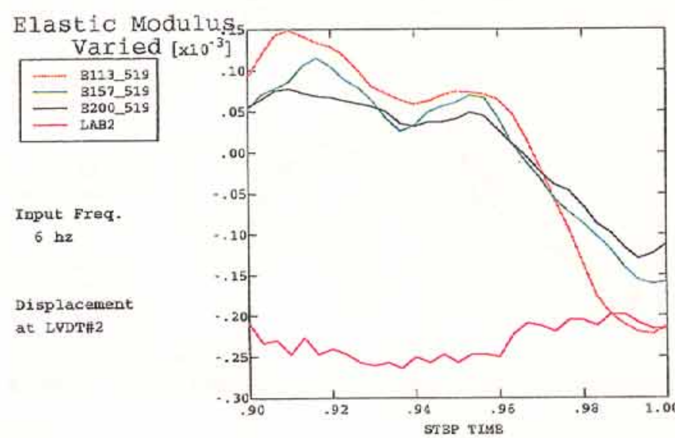


Figure 921

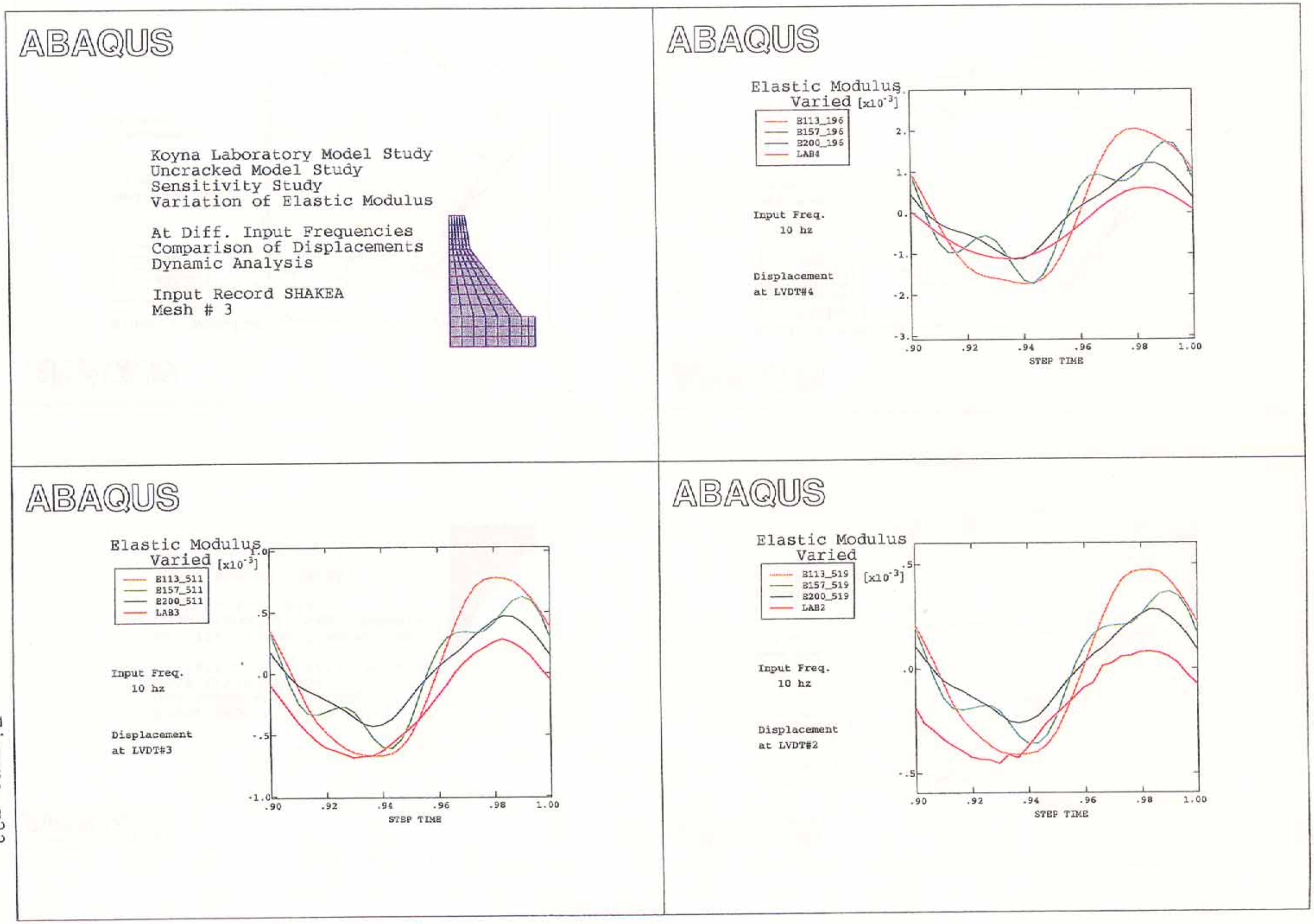

ABAQUS
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus
At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis
Input Record SHAKEA
Mesh # 3
ABAQUS
Elastic Modulus Varied [x10^-3]
B113_196
B157_196
B200_196
LAB4
Input Freq. 10 hz
Displacement at LVDT#4
2.
1.
0.
-1.
-2.
-3.
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS
Elastic Modulus Varied [x10^-3]
B113_511
B157_511
B200_511
LAB3
Input Freq. 10 hz
Displacement at LVDT#3
1.0
.5
.0
-.5
-1.0
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS
Elastic Modulus Varied [x10^-3]
B113_519
B157_519
B200_519
LAB2
Input Freq. 10 hz
Displacement at LVDT#2
.5
.0
-.5
.90
.92
.94
.96
.98
1.00
STEP TIME

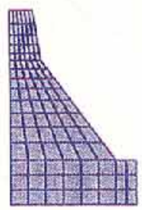
Figure g22

ABAQUS

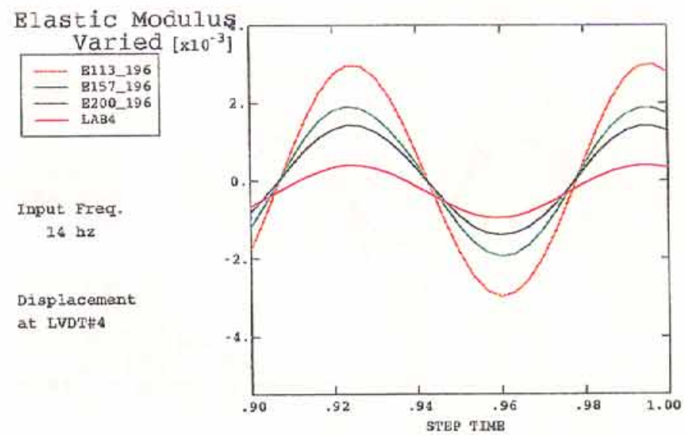
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus

At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis

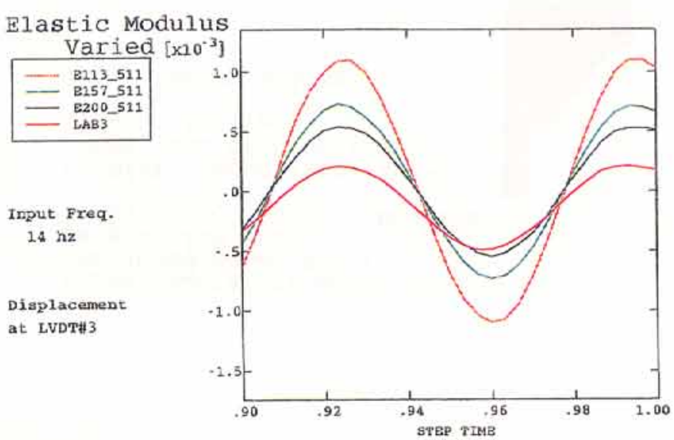
Input Record SHAKEA
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

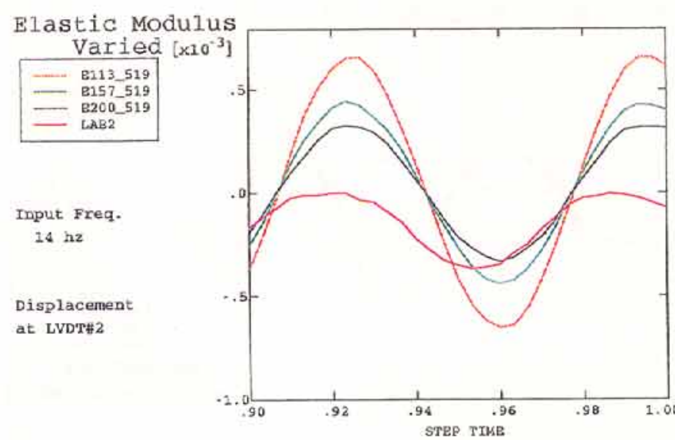


Figure 923

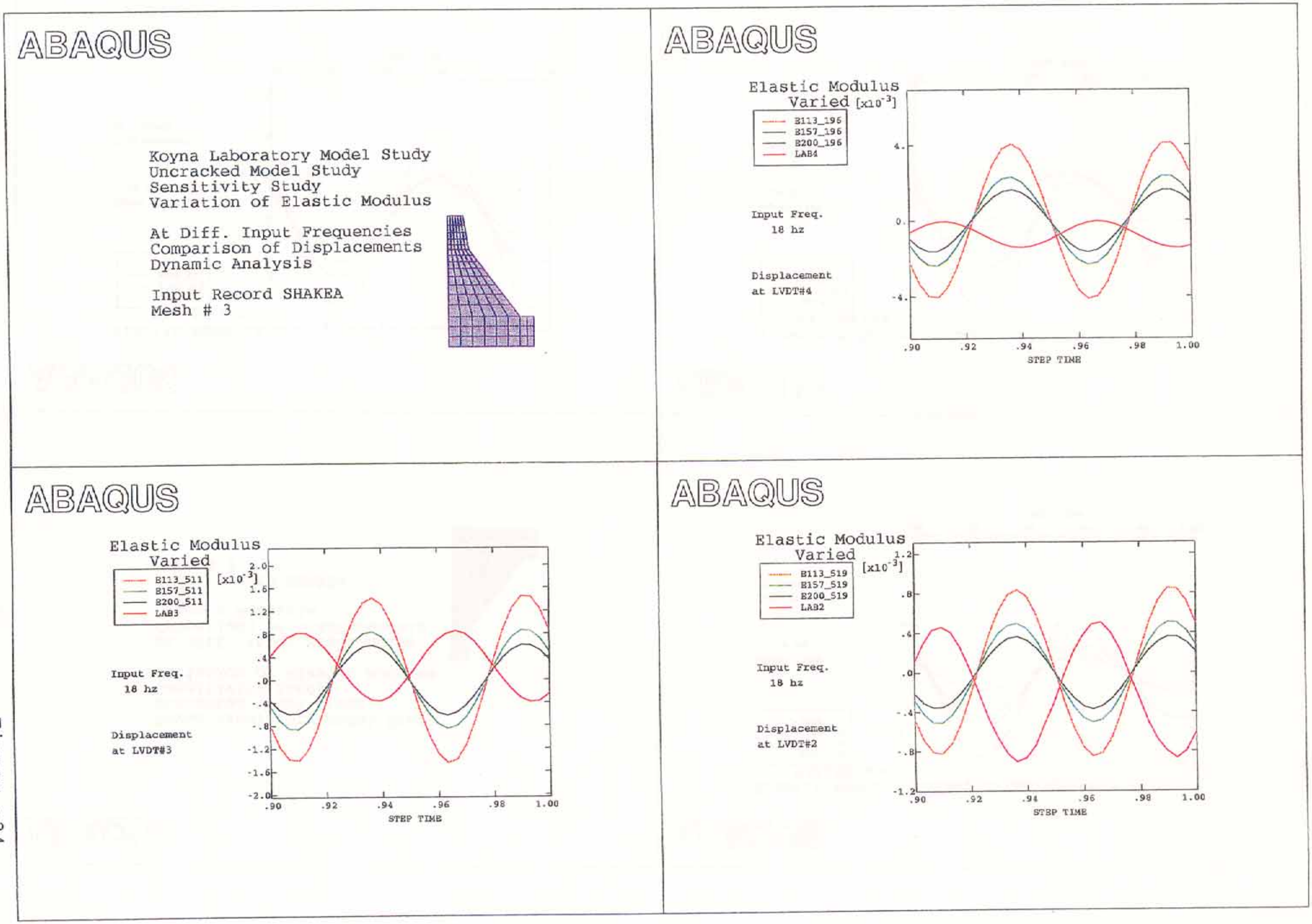

ABAQUS
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus
At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis
Input Record SHAKEA
Mesh # 3
ABAQUS
Elastic Modulus Varied
[x10^-3]
B113_196
B157_196
B200_196
LAB4
Input Freq.
18 hz
Displacement at LVDT#4
4.
0.
-4.
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
[x10^-3]
B113_511
B157_511
B200_511
LAB3
Input Freq.
18 hz
Displacement at LVDT#3
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS
Elastic Modulus Varied
[x10^-3]
B113_519
B157_519
B200_519
LAB2
Input Freq.
18 hz
Displacement at LVDT#2
1.2
.8
.4
.0
-.4
-.8
-1.2
.90
.92
.94
.96
.98
1.00
STEP TIME

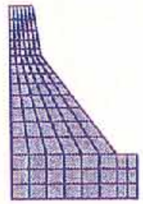
Figure g24

ABAQUS

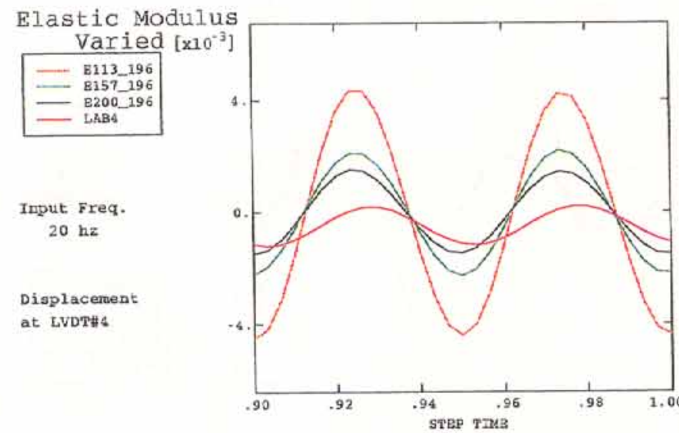
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus

At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis

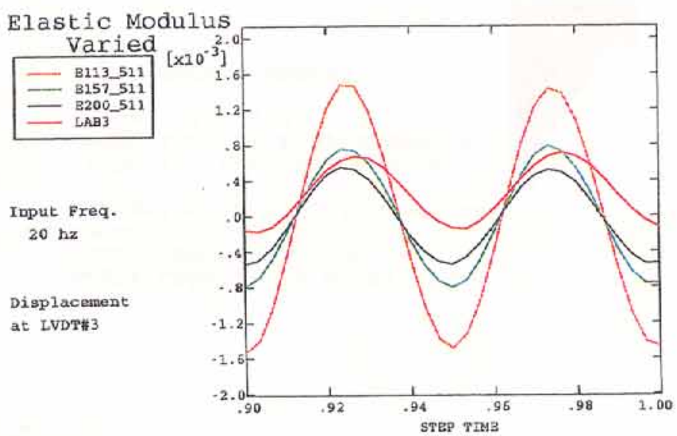
Input Record SHAKEA
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

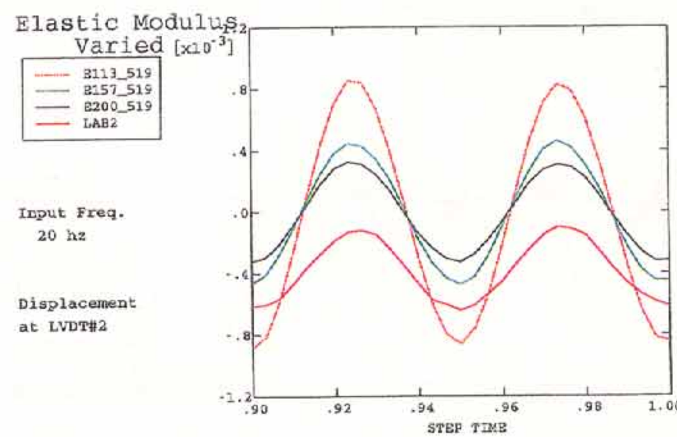


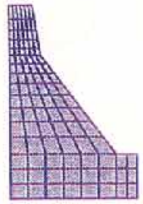
Figure 925

ABAQUS

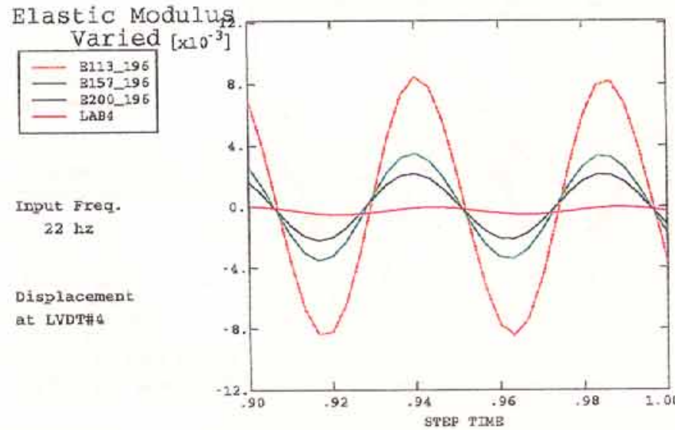
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus

At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis

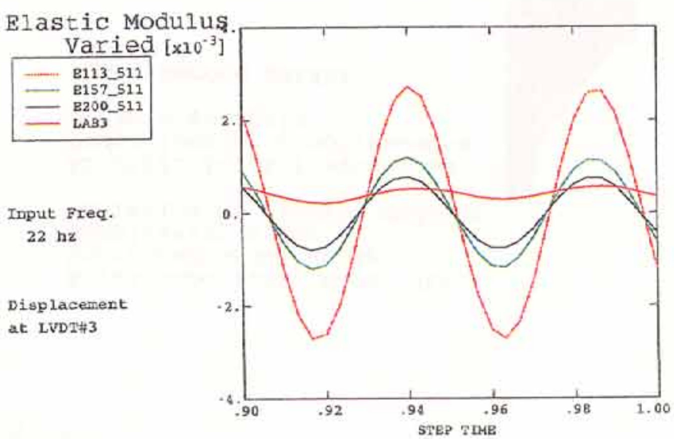
Input Record SHAKEA
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

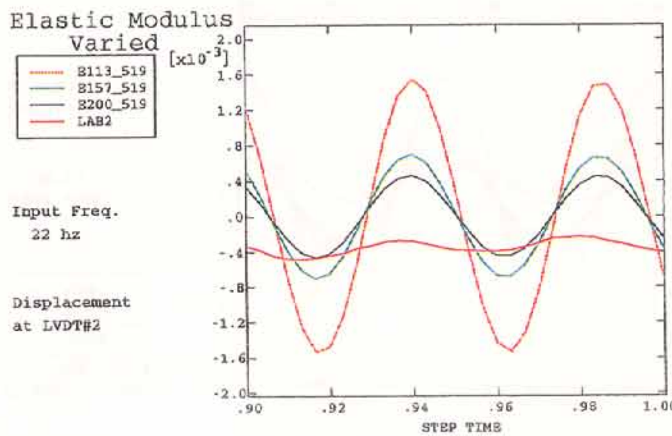


Figure g26

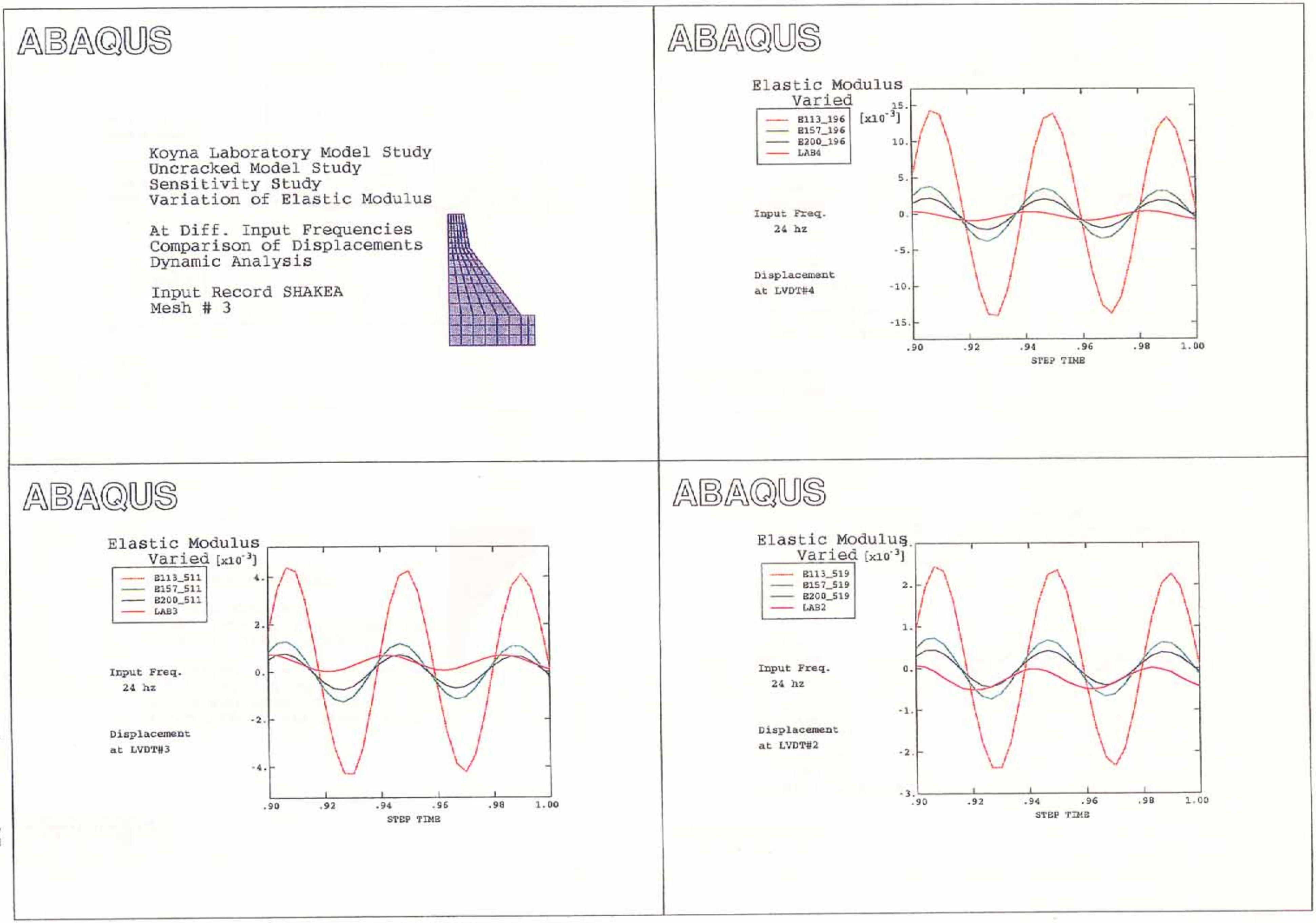

ABAQUS
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus
At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis
Input Record SHAKEA
Mesh # 3
ABAQUS
Elastic Modulus
Varied
B113_196
B157_196
B200_196
LAB4
[x10^-3]
Input Freq.
24 hz
Displacement
at LVDT#4
STEP TIME
ABAQUS
Elastic Modulus
Varied [x10^-3]
B113_511
B157_511
B200_511
LAB3
Input Freq.
24 hz
Displacement
at LVDT#3
STEP TIME
ABAQUS
Elastic Modulus
Varied [x10^-3]
B113_519
B157_519
B200_519
LAB2
Input Freq.
24 hz
Displacement
at LVDT#2
STEP TIME

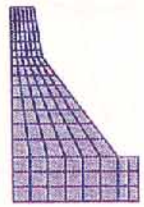
Figure 927

ABAQUS

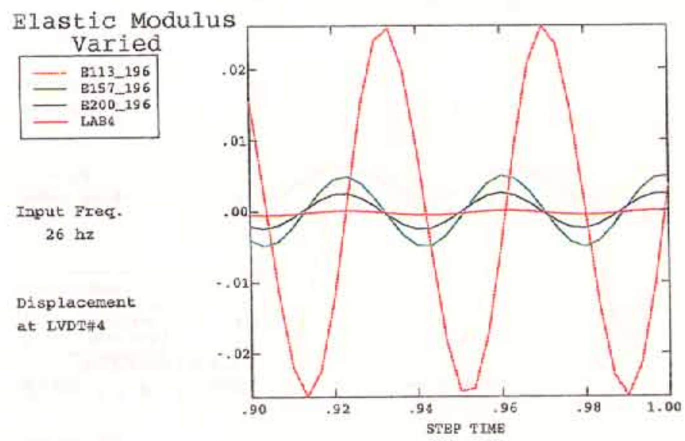
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Elastic Modulus

At Diff. Input Frequencies
Comparison of Displacements
Dynamic Analysis

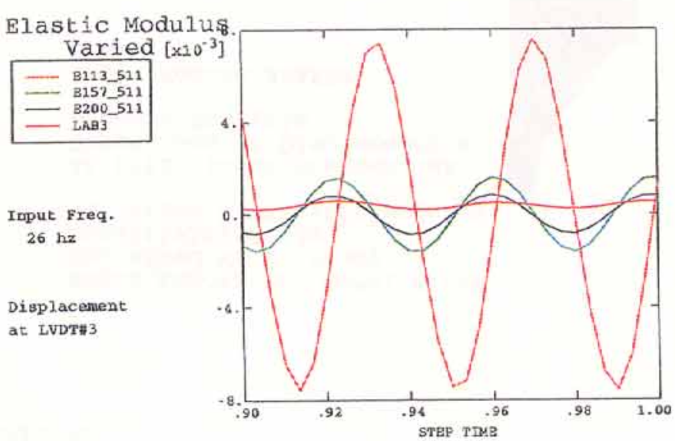
Input Record SHAKEA
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

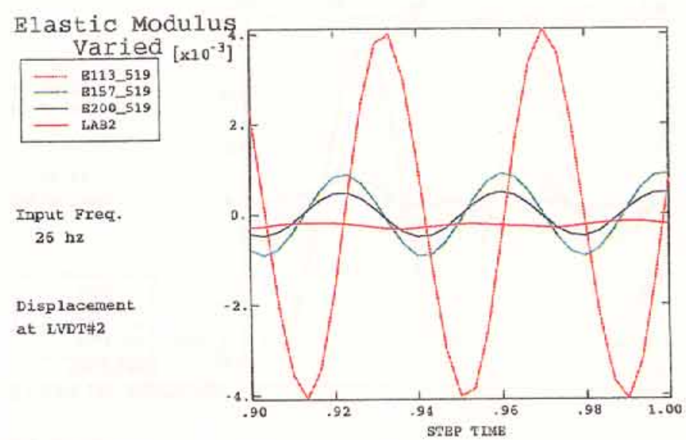


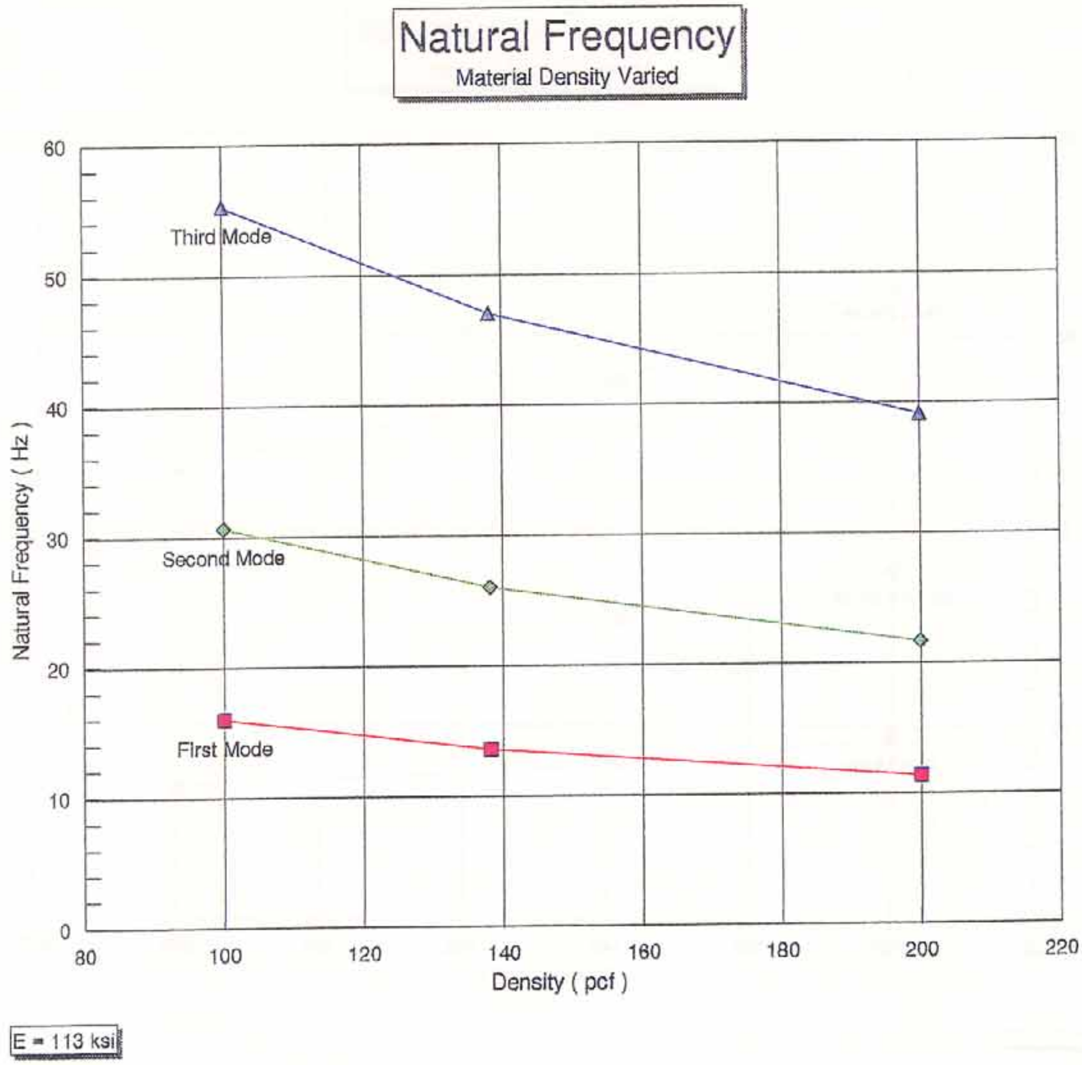
Figure 928

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

Elastic Modulus = 113 ksi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Natural Frequencies (Hz)				
Mode	100	138.2	200	LAB
1	16.0	13.6	11.3	18.0
2	30.6	26.0	21.6	24.0
3	55.3	47.0	39.1	30.0
4	65.8	55.9	46.5	
5	68.7	58.4	48.5	
6	70.8	60.2	50.1	
7	75.2	64.0	53.2	
8	76.2	64.8	53.9	
9	76.9	65.4	54.4	
10	78.4	66.7	55.4	

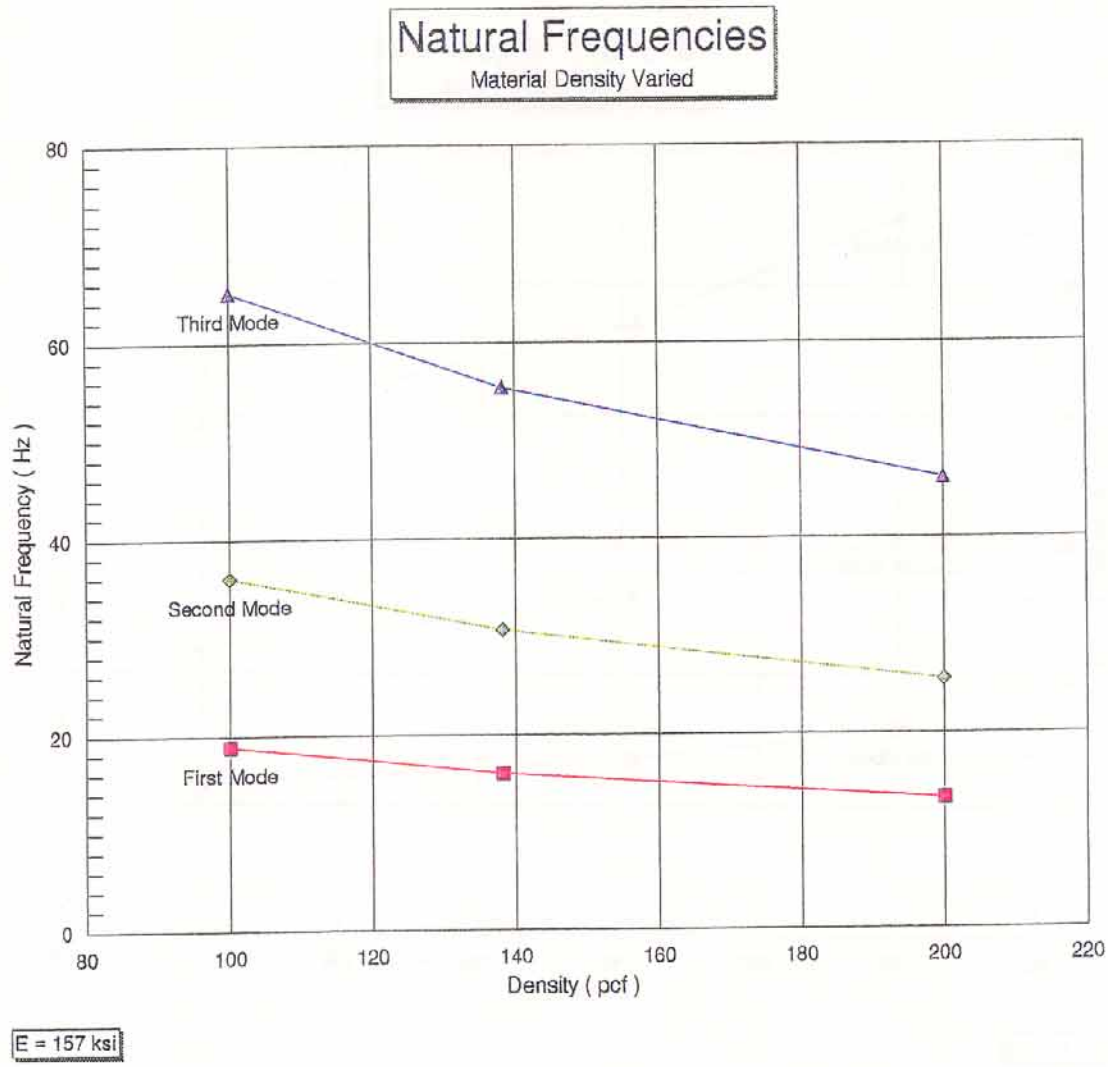
Figure g29

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

Elastic Modulus = 157 ksi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleight Damping Factors



Natural Frequenies (Hz)				
Mode	100	138.2	200	LAB
1	18.8	16.0	13.3	18.0
2	36.0	30.6	25.5	22.0
3	65.1	55.4	46.1	30.0
4	77.5	65.9	54.8	
5	80.9	68.8	57.2	
6	83.5	71.0	59.0	
7	88.7	75.4	62.7	
8	89.8	76.4	63.5	
9	90.6	77.1	64.1	
10	92.4	78.6	65.3	

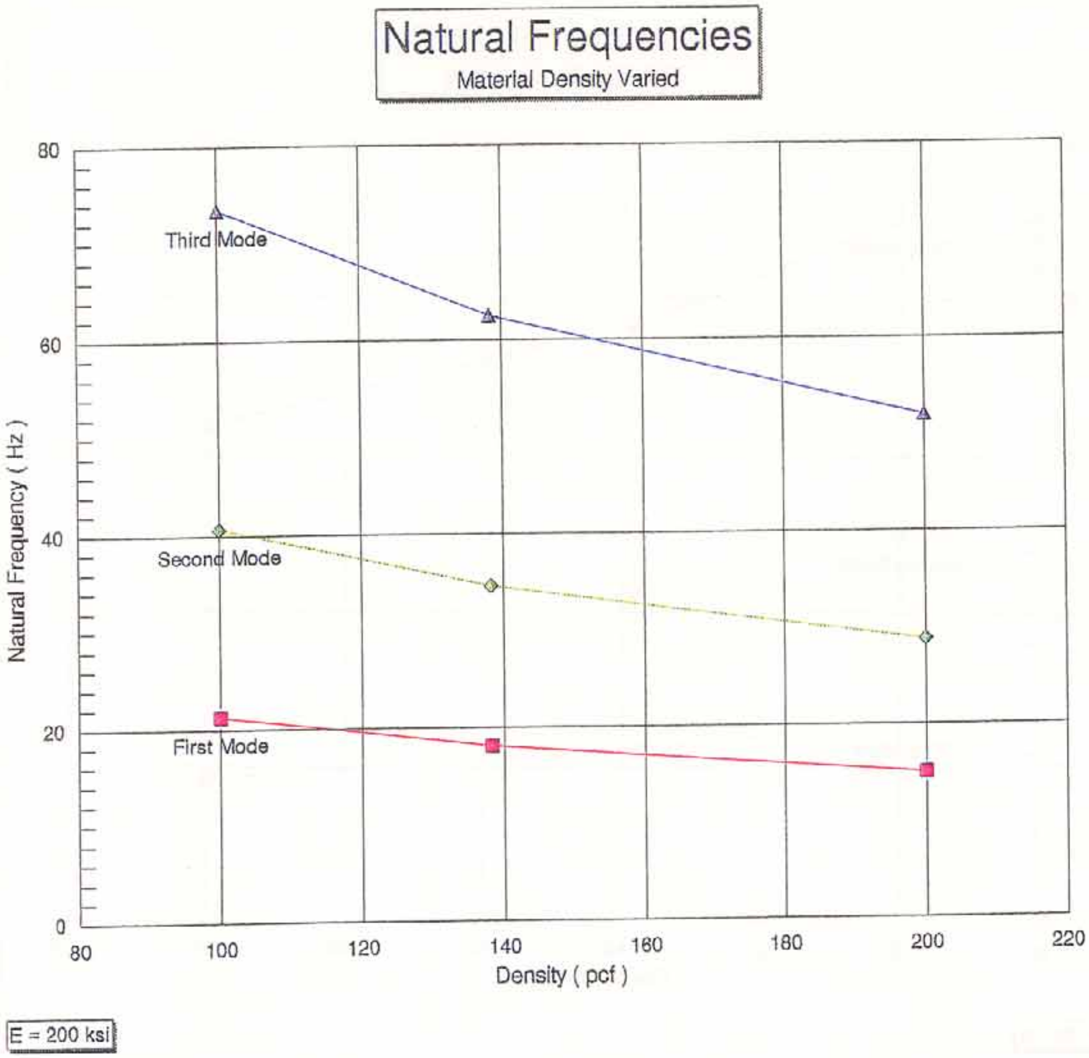
Figure g30

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

Elastic Modulus = 200 ksi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Natural Frequenies (Hz)				
Mode	100	138.2	200	LAB
1	21.3	18.1	15.0	18.0
2	40.7	34.6	28.7	24.0
3	73.5	62.5	52.0	30.0
4	87.5	74.4	61.9	
5	91.3	77.7	64.6	
6	94.2	80.1	66.6	
7	100.1	85.1	70.8	
8	101.3	86.2	71.6	
9	102.3	87.0	72.3	
10	104.3	88.7	73.7	

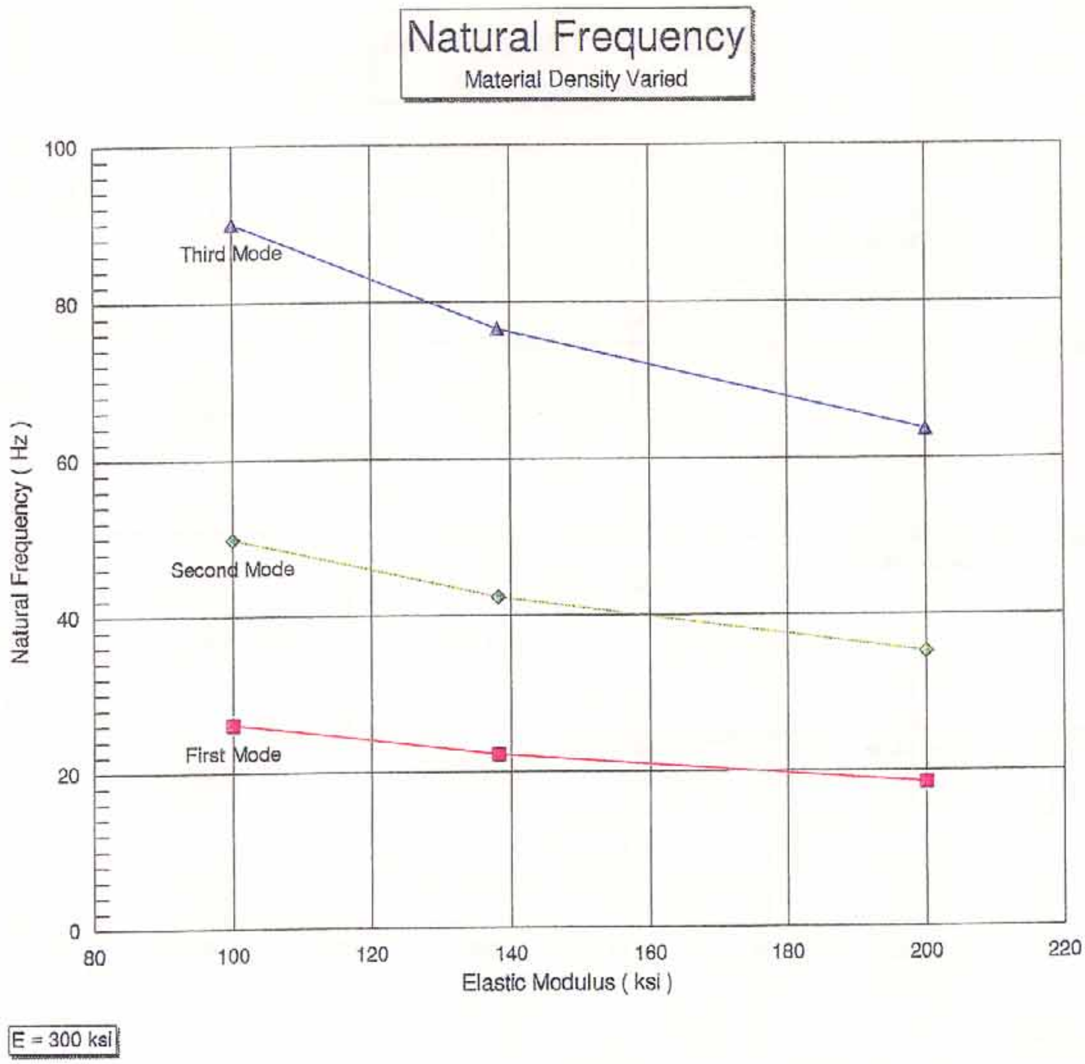
Figure g31

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

Elastic Modulus = 300 ksi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Natural Frequenies (Hz)				
Mode	100	138.2	200	LAB
1	26.0	22.2	18.4	18.0
2	49.8	42.4	35.2	24.0
3	90.0	76.6	63.7	30.0
4	107.2	91.1	75.8	
5	111.9	95.2	79.1	
6	115.4	98.1	81.6	
7	122.5	104.2	86.7	
8	124.1	105.6	87.7	
9	125.3	106.6	88.6	
10	127.7	108.7	90.3	

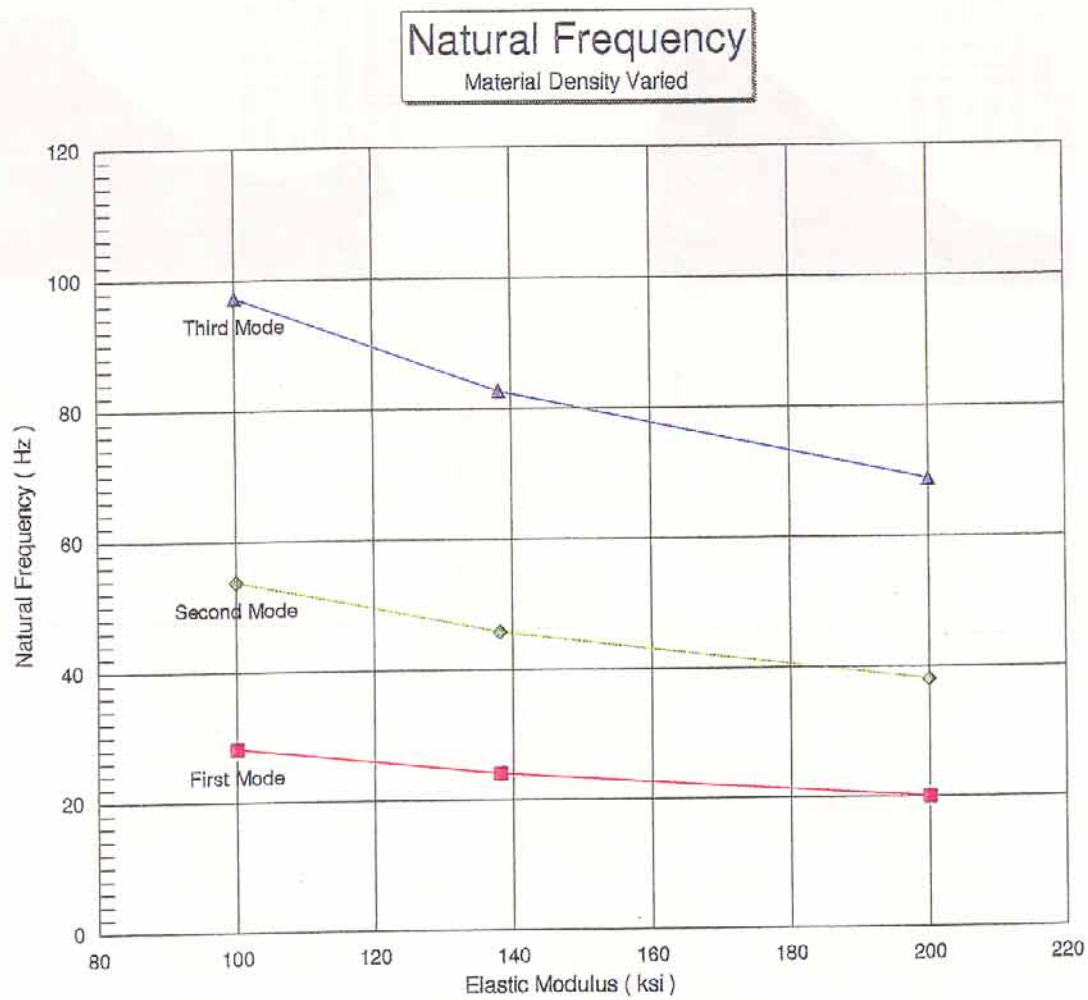
Figure g32

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

Elastic Modulus = 350 ksi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



E = 350 ksi

Natural Frequencies (Hz)				
Mode	100	138.2	200	LAB
1	28.1	24.0	19.9	18.0
2	53.8	45.7	38.0	24.0
3	97.2	82.7	68.8	30.0
4	115.7	98.4	81.8	
5	120.8	102.8	85.4	
6	124.6	106.0	88.1	
7	132.4	112.6	93.6	
8	134.0	114.0	94.8	
9	135.3	115.1	95.7	
10	138.0	117.4	97.6	

Figure g33

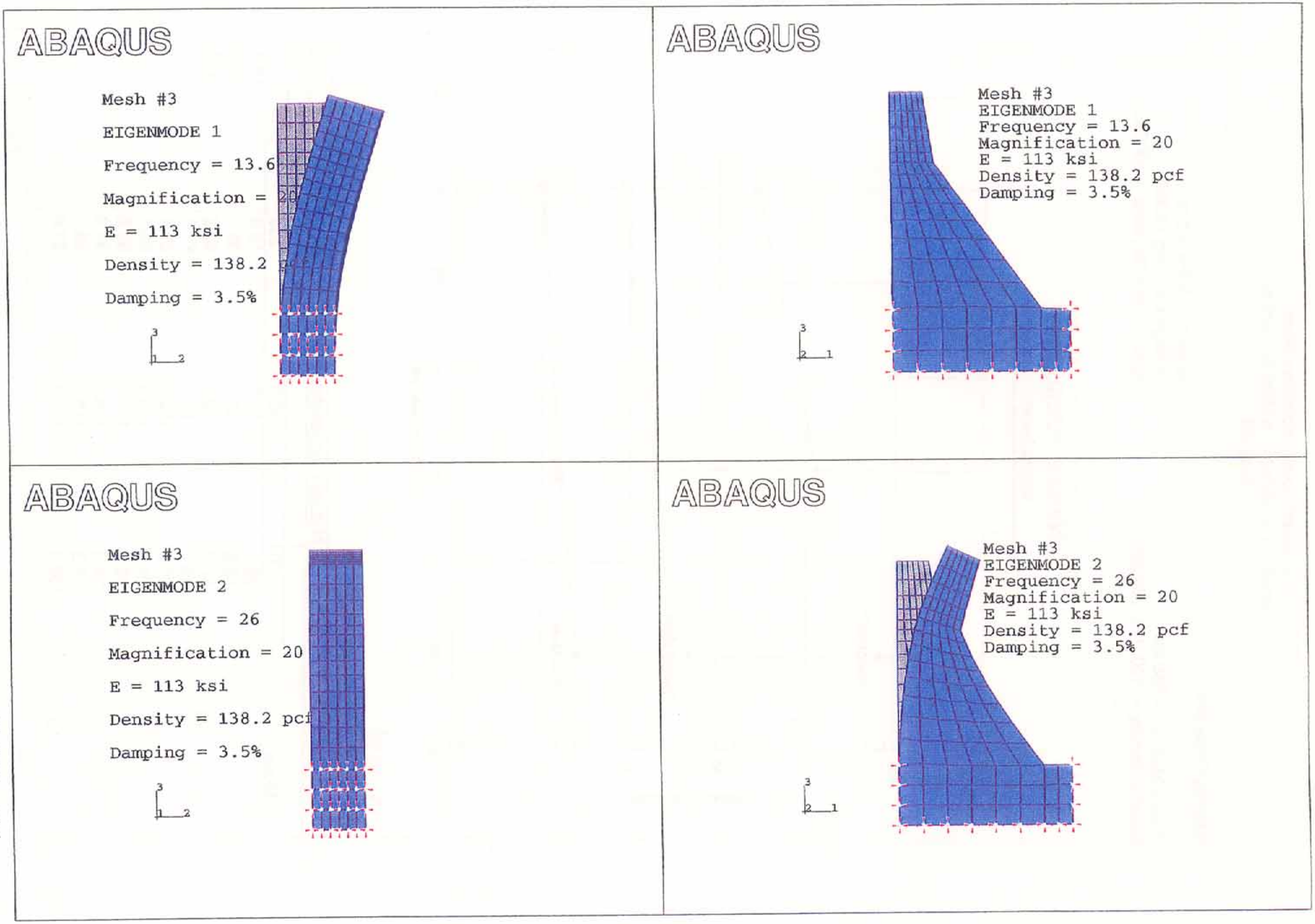

ABAQUS
Mesh #3
EIGENMODE 1
Frequency = 13.6
Magnification = 20
E = 113 ksi
Density = 138.2 pcf
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 1
Frequency = 13.6
Magnification = 20
E = 113 ksi
Density = 138.2 pcf
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 2
Frequency = 26
Magnification = 20
E = 113 ksi
Density = 138.2 pcf
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 2
Frequency = 26
Magnification = 20
E = 113 ksi
Density = 138.2 pcf
Damping = 3.5%

Figure g34

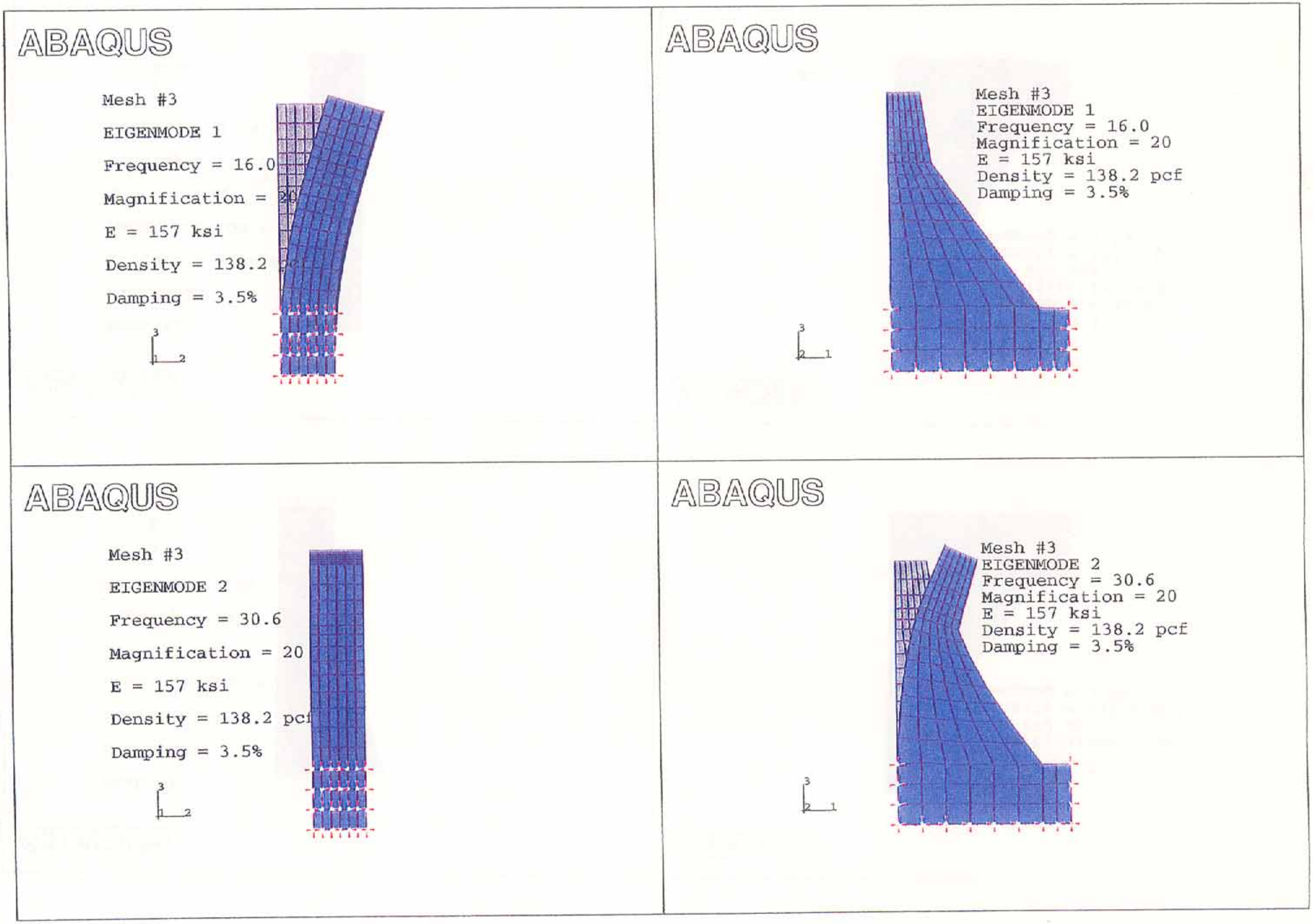

ABAQUS
Mesh #3
EIGENMODE 1
Frequency = 16.0
Magnification = 20
E = 157 ksi
Density = 138.2 pcf
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 1
Frequency = 16.0
Magnification = 20
E = 157 ksi
Density = 138.2 pcf
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 2
Frequency = 30.6
Magnification = 20
E = 157 ksi
Density = 138.2 pcf
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 2
Frequency = 30.6
Magnification = 20
E = 157 ksi
Density = 138.2 pcf
Damping = 3.5%

Figure g35

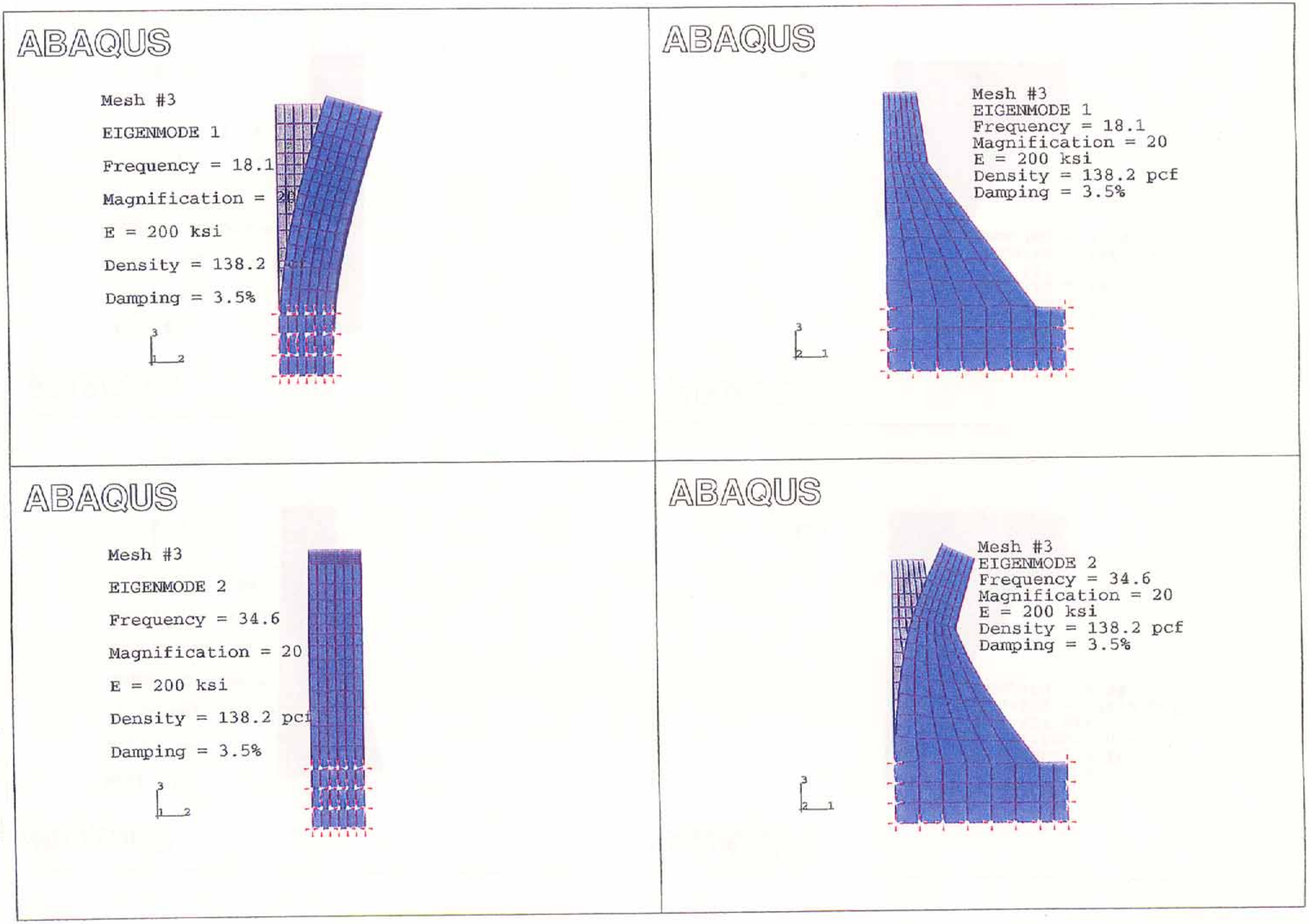

ABAQUS
Mesh #3
EIGENMODE 1
Frequency = 18.1
Magnification =
E = 200 ksi
Density = 138.2
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 1
Frequency = 18.1
Magnification = 20
E = 200 ksi
Density = 138.2 pcf
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 2
Frequency = 34.6
Magnification = 20
E = 200 ksi
Density = 138.2 pc
Damping = 3.5%
ABAQUS
Mesh #3
EIGENMODE 2
Frequency = 34.6
Magnification = 20
E = 200 ksi
Density = 138.2 pcf
Damping = 3.5%

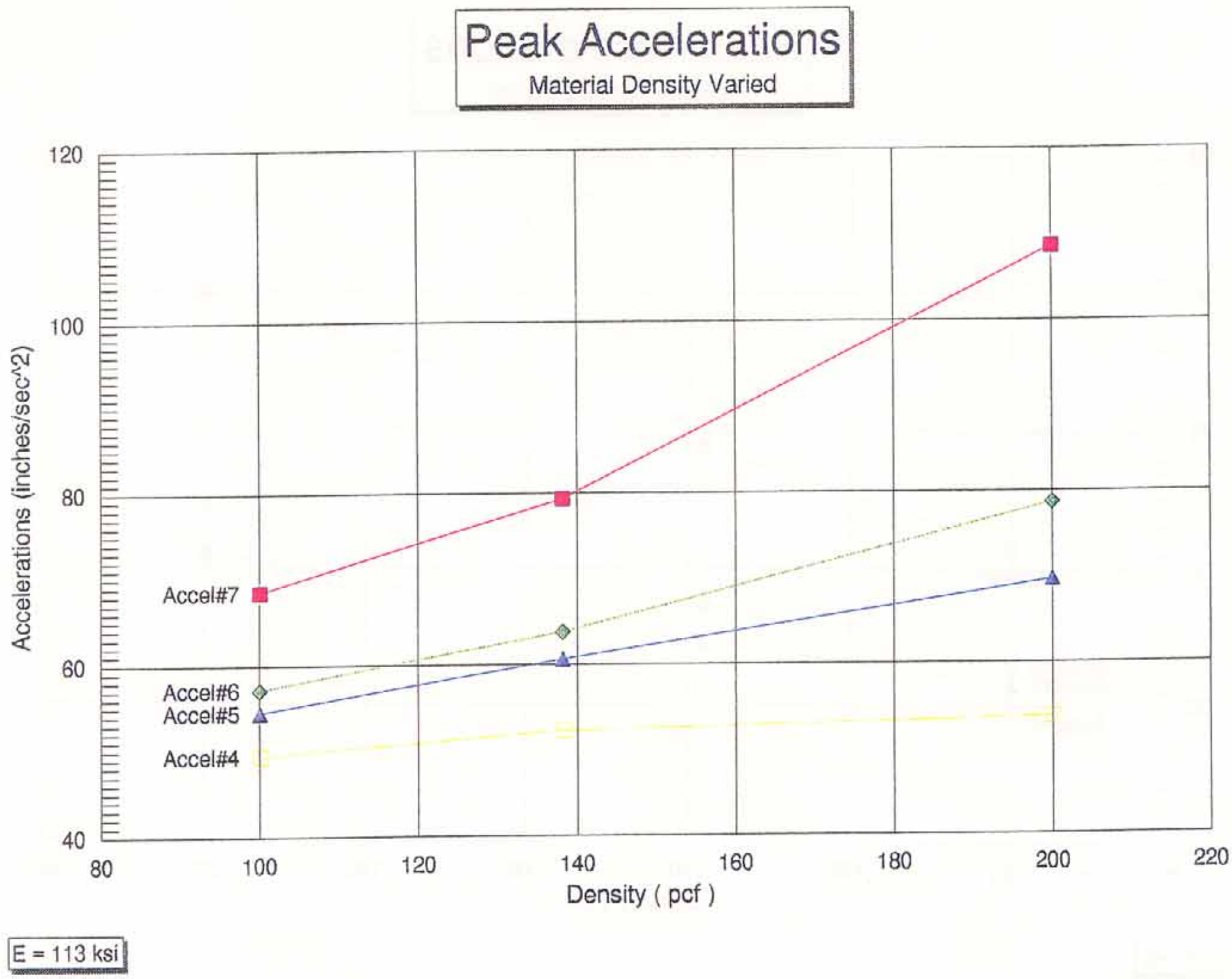
Figure g36

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 113,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

	100	138.2	200	LAB
Accel#7	68.51	79.31	108.60	53.26
Accel#6	57.18	63.80	78.68	51.72
Accel#5	54.49	60.60	69.67	49.26
Accel#4	49.40	52.28	53.65	47.72

Figure g37

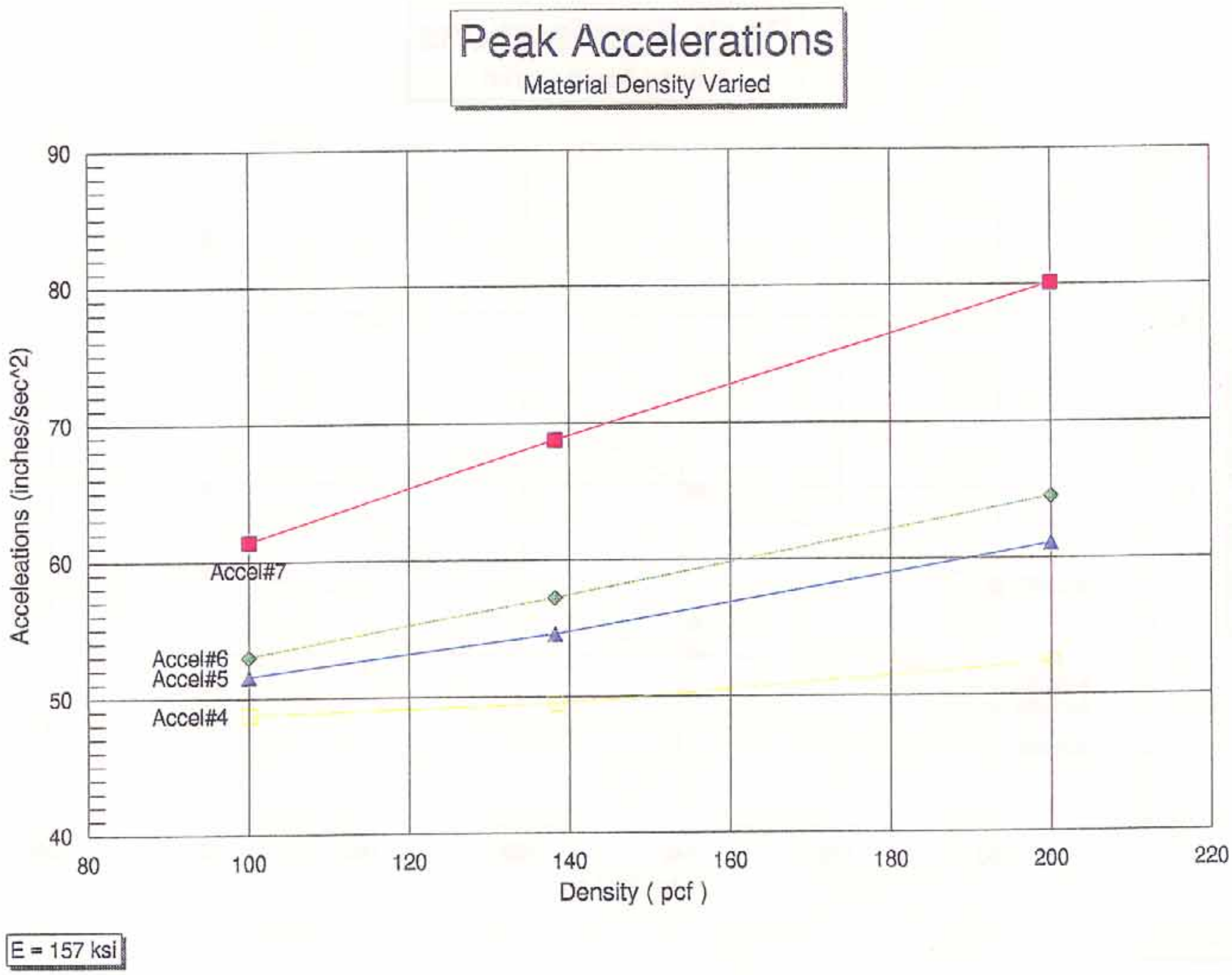
Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 157,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical

Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

	100	138.2	200	LAB
Accel#7	61.39	68.75	80.10	53.26
Accel#6	52.99	57.19	64.49	51.72
Accel#5	51.54	54.54	61.04	49.26
Accel#4	48.70	49.47	52.36	47.72

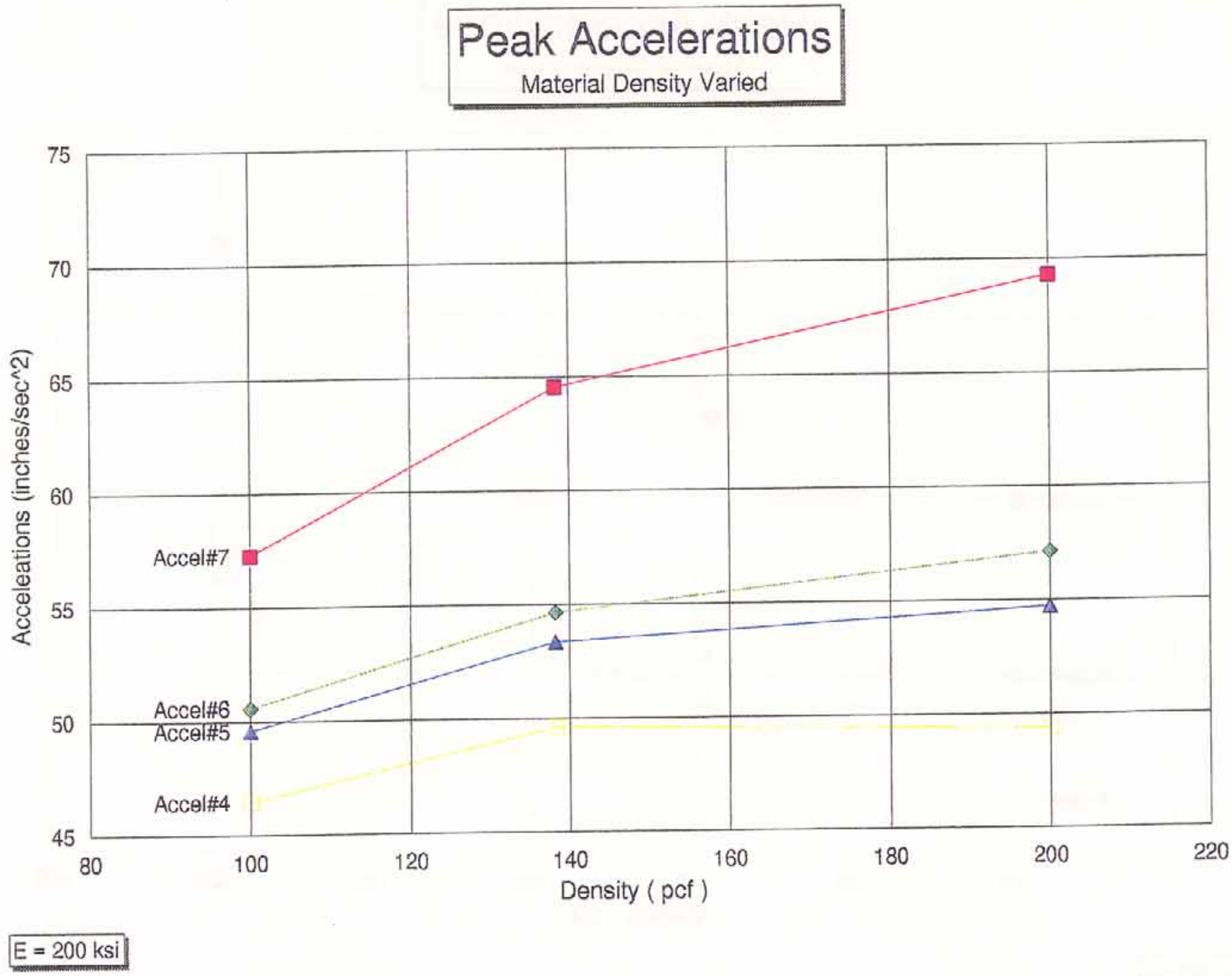
Figure g38

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 200,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

	100	138.2	200	LAB
Accel#7	57.25	64.53	69.27	53.26
Accel#6	50.56	54.64	57.12	51.72
Accel#5	49.57	53.34	54.73	49.26
Accel#4	46.42	49.60	49.36	47.72

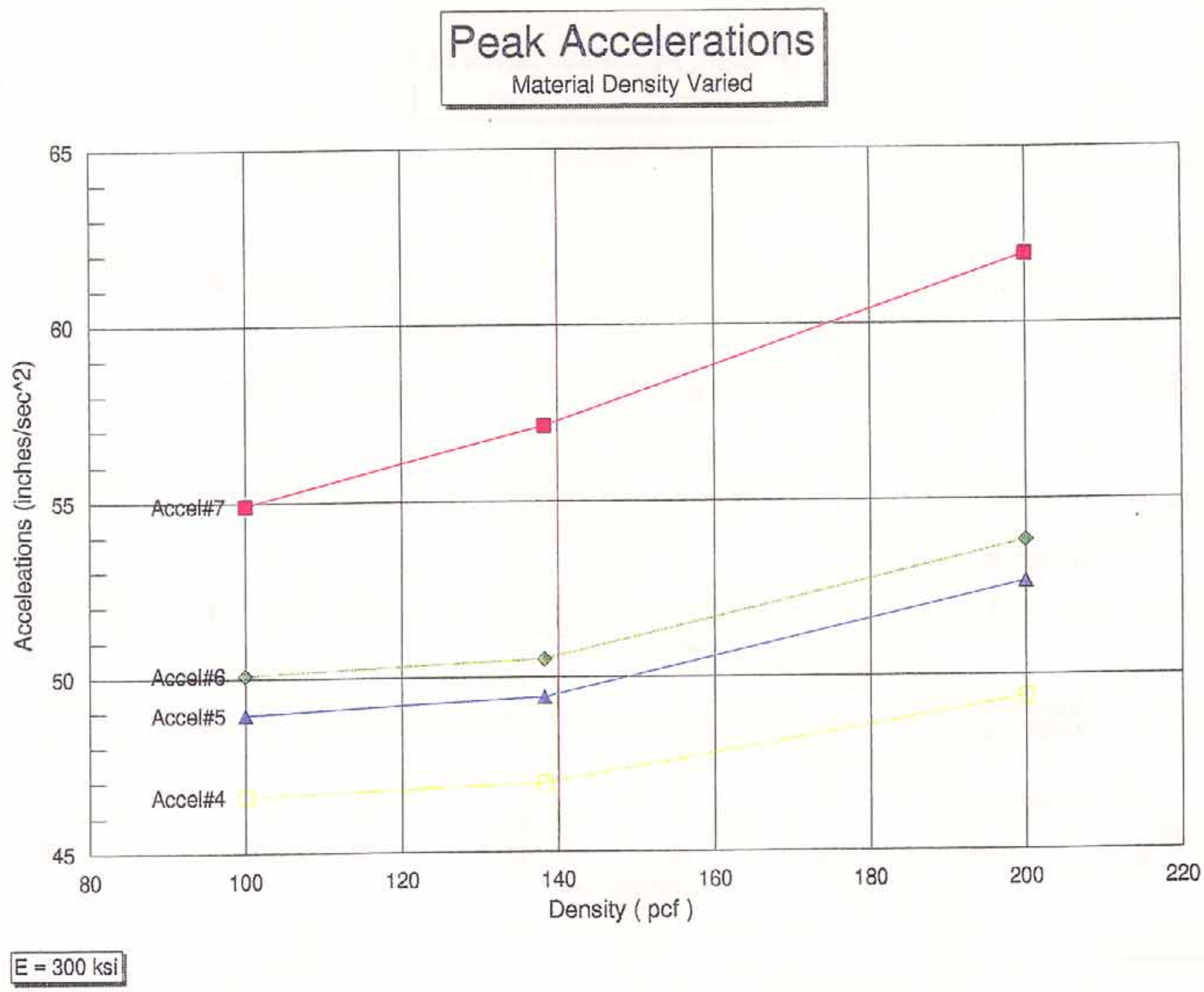
Figure g39

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 300,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

	100	138.2	200	LAB
Accel#7	54.90	57.14	61.96	53.26
Accel#6	50.07	50.50	53.82	51.72
Accel#5	48.93	49.42	52.65	49.26
Accel#4	46.59	46.97	49.36	47.72

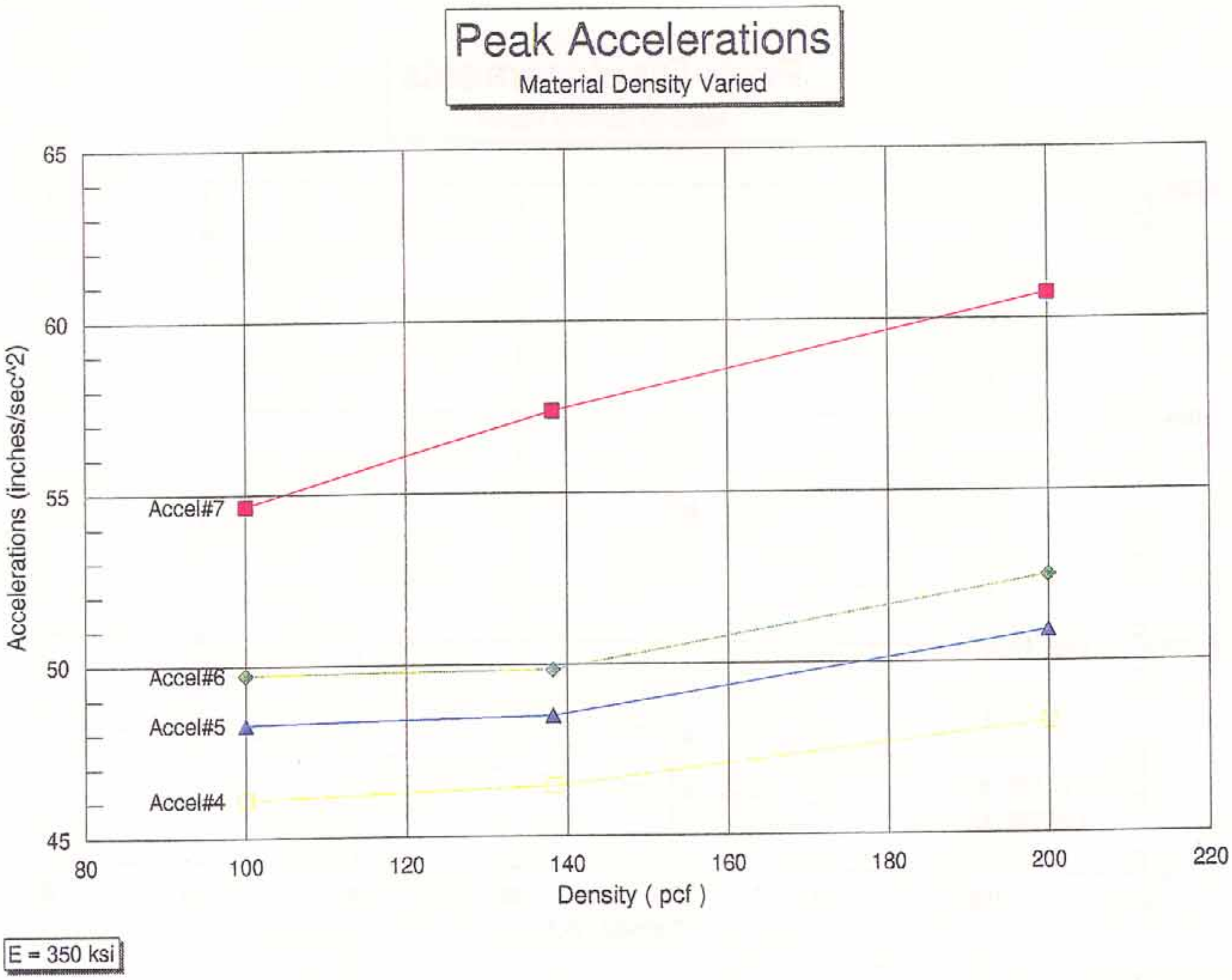
Figure g40

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 350,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Accelerations (inch / sec ^ 2)

	100	138.2	200	LAB
Accel#7	54.66	57.39	60.74	53.26
Accel#6	49.73	49.85	52.52	51.72
Accel#5	48.29	48.51	50.91	49.26
Accel#4	46.09	46.47	48.24	47.72

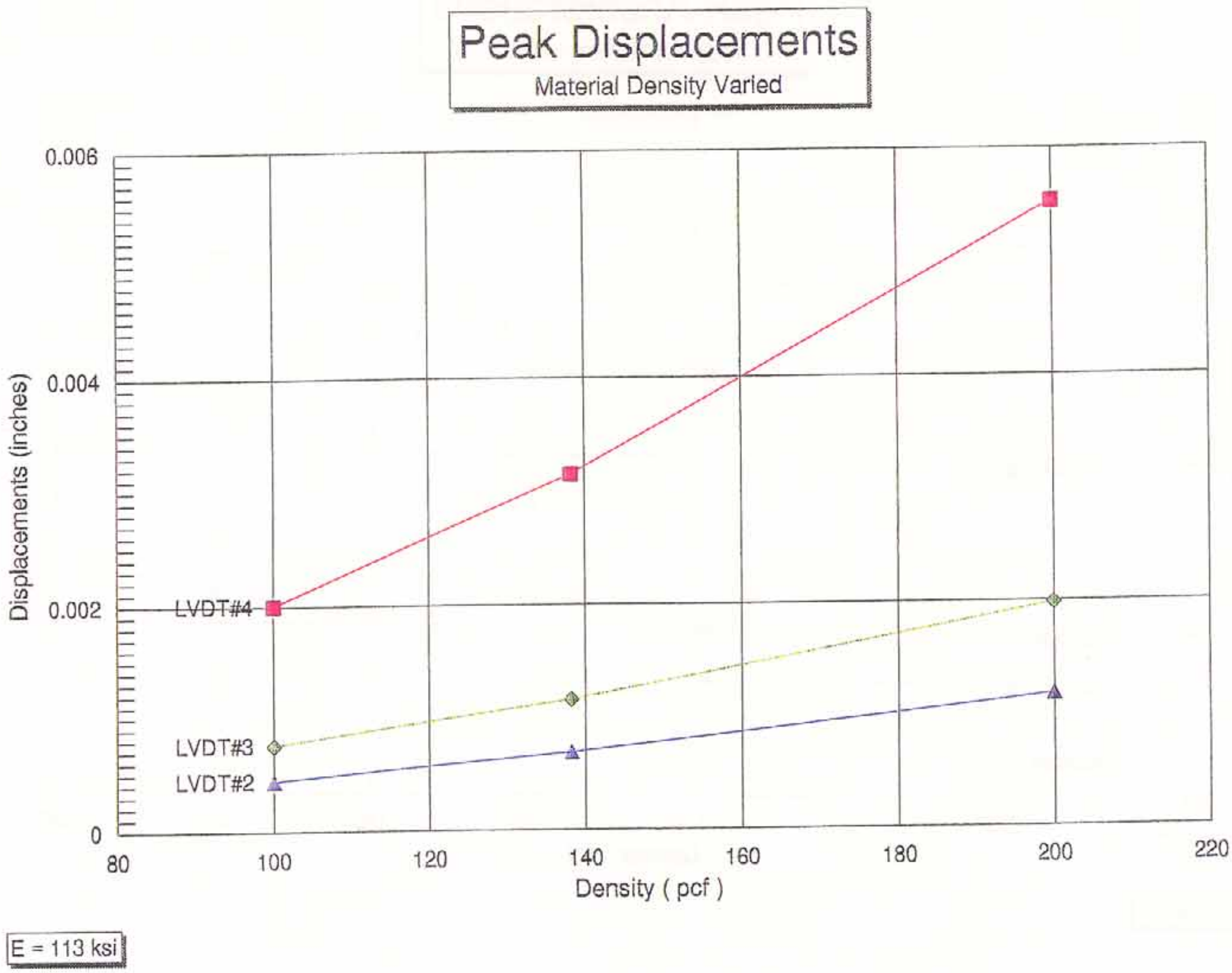
Figure g41

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 113,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (inches)				
	100	138.2	200	LAB
LVDT#4	2.0E-03	3.1E-03	5.5E-03	7.2E-04
LVDT#3	7.6E-04	1.2E-03	2.0E-03	3.1E-04
LVDT#2	4.5E-04	6.9E-04	1.2E-03	2.1E-04

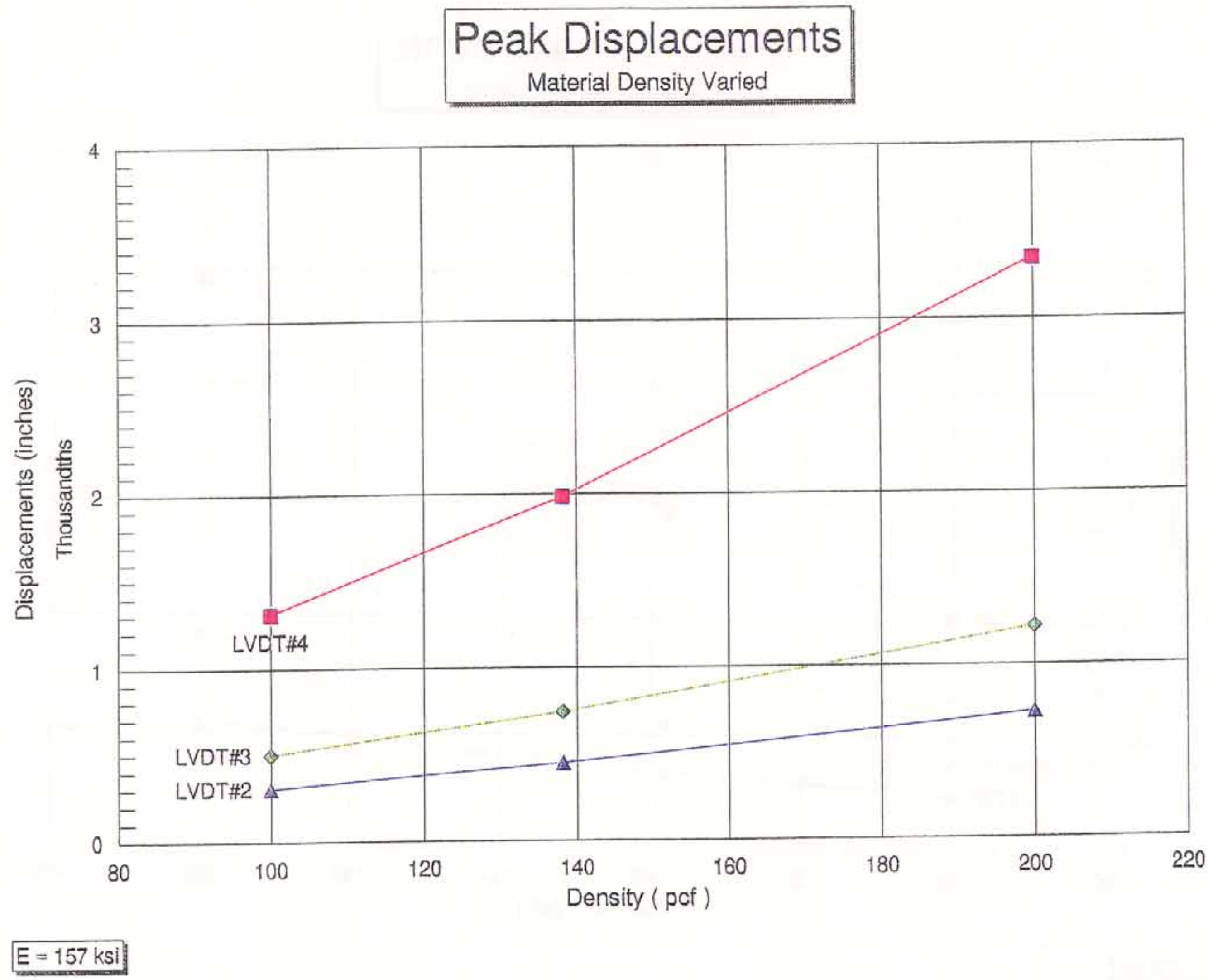
Figure g42

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 157,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (inches)

	100	138.2	200	LAB
LVDT#4	1.3E-03	2.0E-03	3.3E-03	7.2E-04
LVDT#3	5.0E-04	7.4E-04	1.2E-03	3.1E-04
LVDT#2	3.0E-04	4.4E-04	7.2E-04	2.1E-04

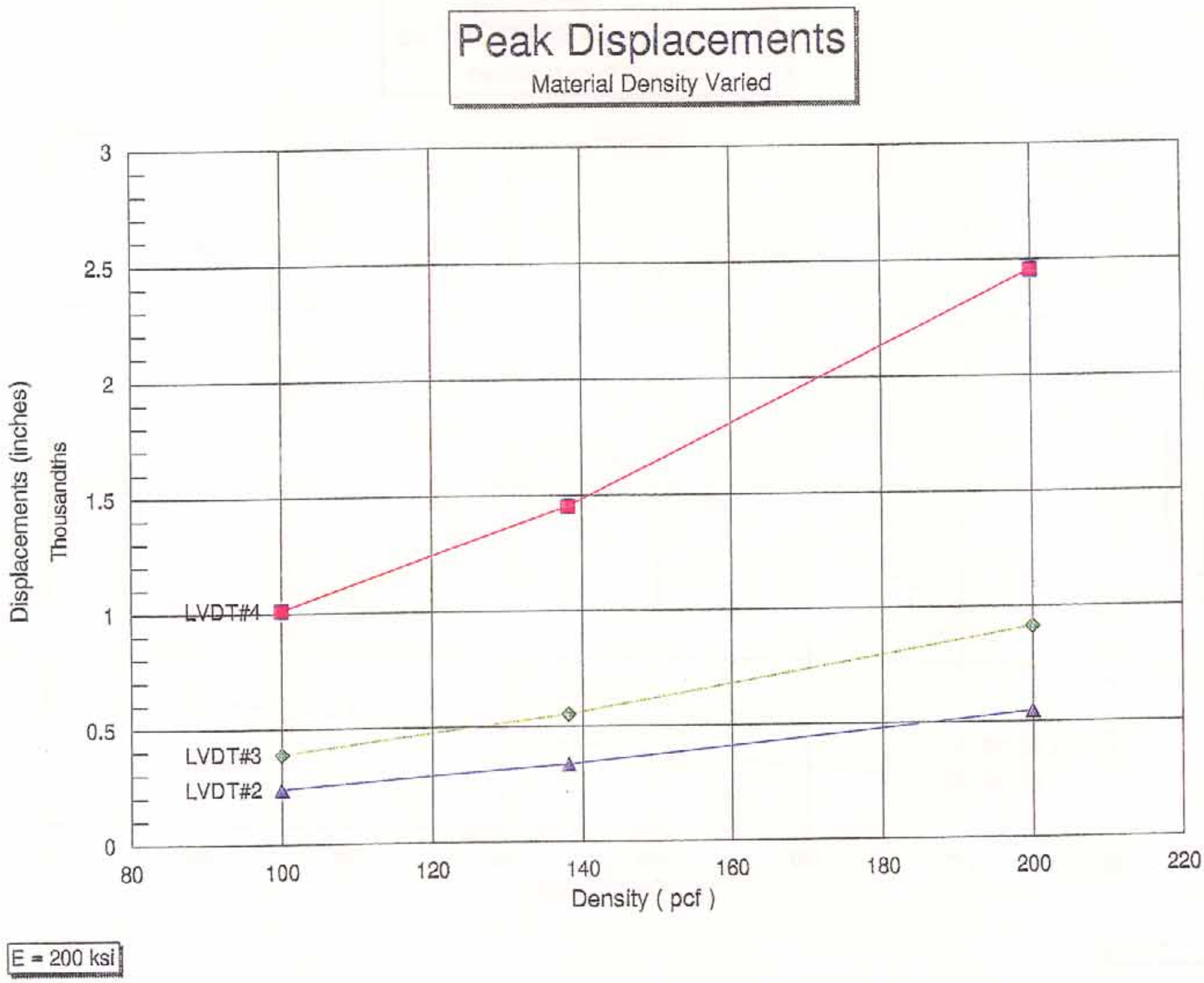
Figure g43

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 200,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (inches)				
	100	138.2	200	LAB
LVDT#4	1.0E-03	1.5E-03	2.5E-03	7.2E-04
LVDT#3	3.9E-04	5.5E-04	9.1E-04	3.1E-04
LVDT#2	2.4E-04	3.3E-04	5.5E-04	2.1E-04

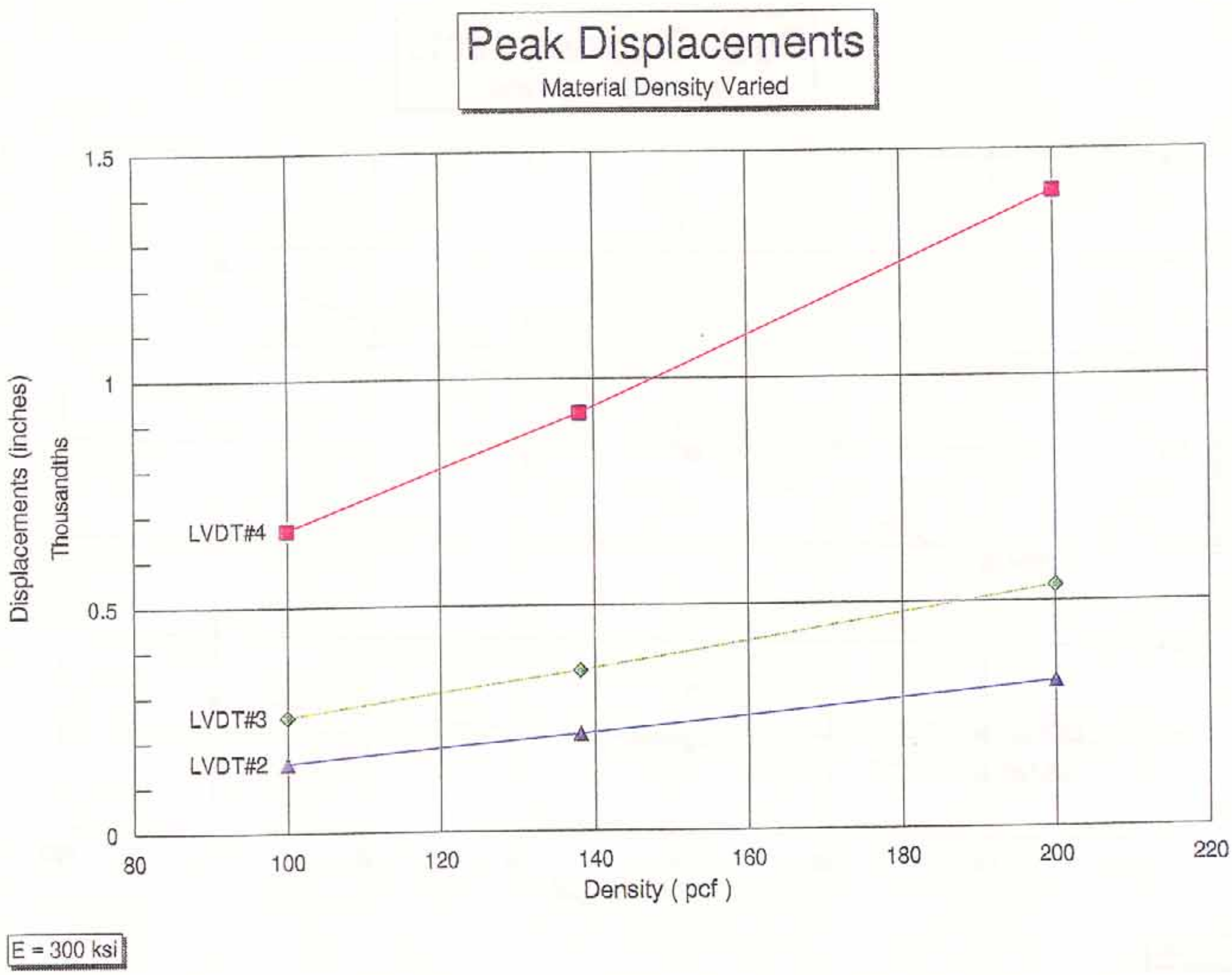
Figure g44

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

E = 300,000 psi
Material Density = (100, 138, 200 pcf)

Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248



Peak Displacements (inches)				
	100	138.2	200	LAB
LVDT#4	6.7E-04	9.2E-04	1.4E-03	7.2E-04
LVDT#3	2.6E-04	3.6E-04	5.3E-04	3.1E-04
LVDT#2	1.5E-04	2.2E-04	3.2E-04	2.1E-04

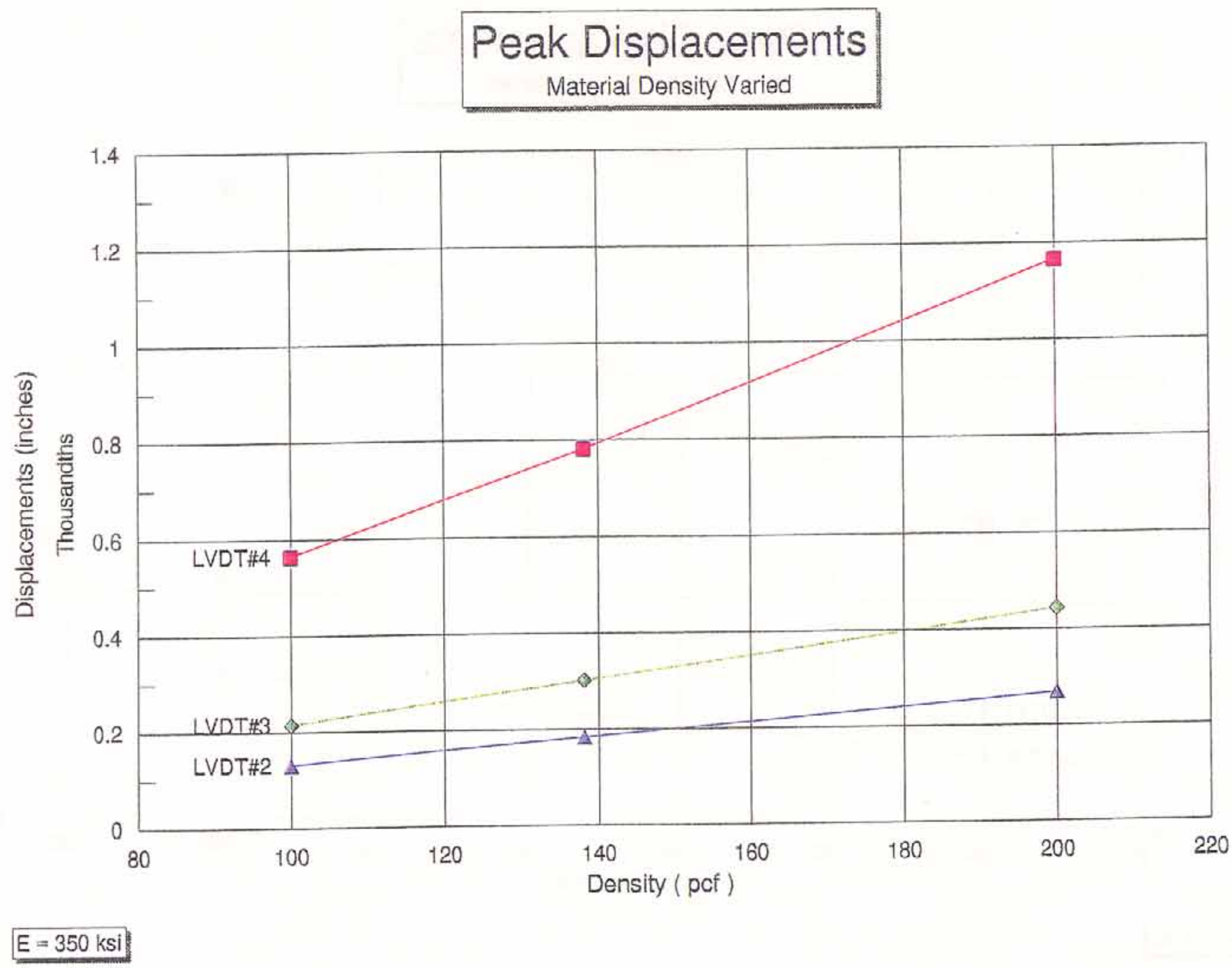
Figure g45

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Material Density
Mesh#3

Material Properties

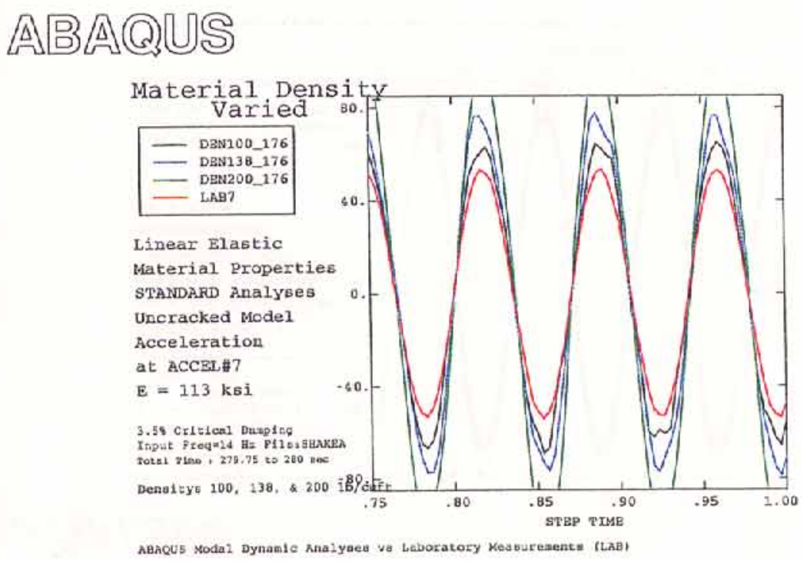
E = 350,000 psi
Material Density = (100, 138, 200 pcf)

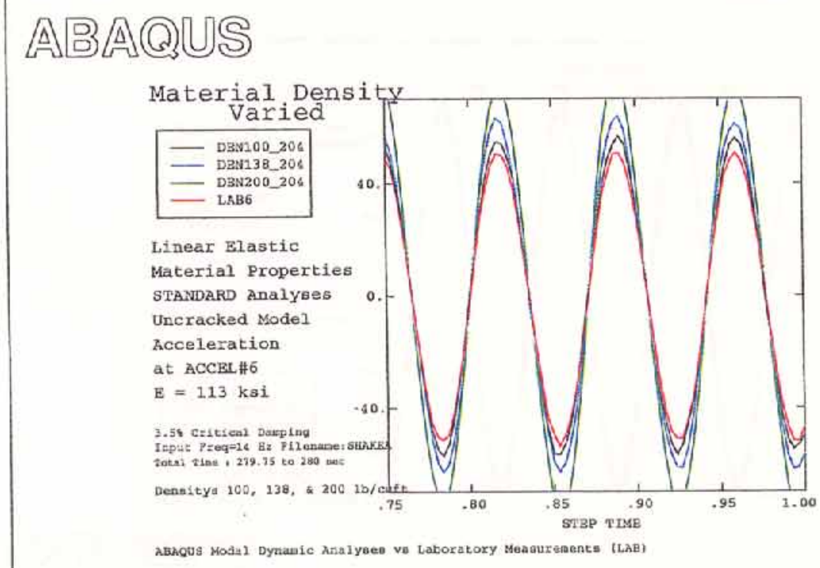
Damping = 3.5% critical
Rayleigh Damping Factors
Alpha = 1.954769; Beta = .000248

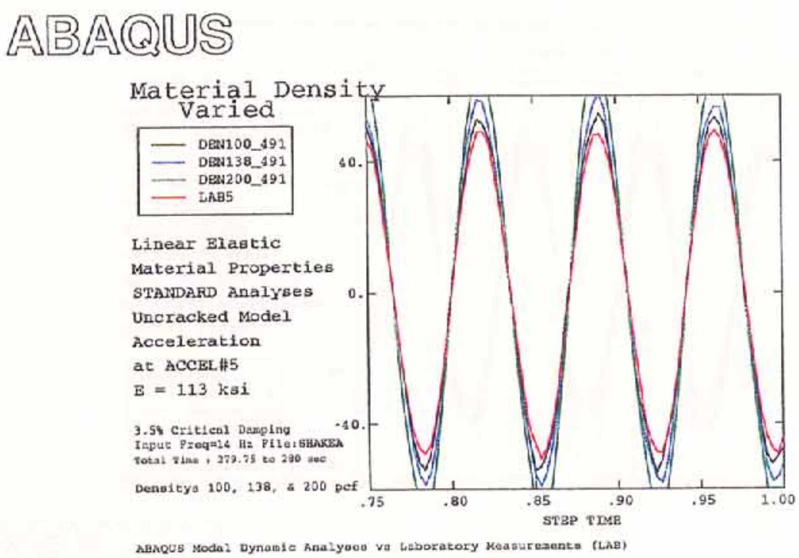


Peak Displacements (inches)				
	100	138.2	200	LAB
LVDT#4	5.6E-04	7.8E-04	1.2E-03	7.2E-04
LVDT#3	2.2E-04	3.0E-04	4.4E-04	3.1E-04
LVDT#2	1.3E-04	1.8E-04	2.7E-04	2.1E-04

Figure g46


ABAQUS
Material Density Varied
DEN100_176
DEN138_176
DEN200_176
LAB7
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
E = 113 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)


ABAQUS
Material Density Varied
DEN100_206
DEN138_206
DEN200_206
LAB6
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
E = 113 ksi
3.5% Critical Damping
Input Freq=14 Hz Filename:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)


ABAQUS
Material Density Varied
DEN100_491
DEN138_491
DEN200_491
LAB5
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
E = 113 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 pcf
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

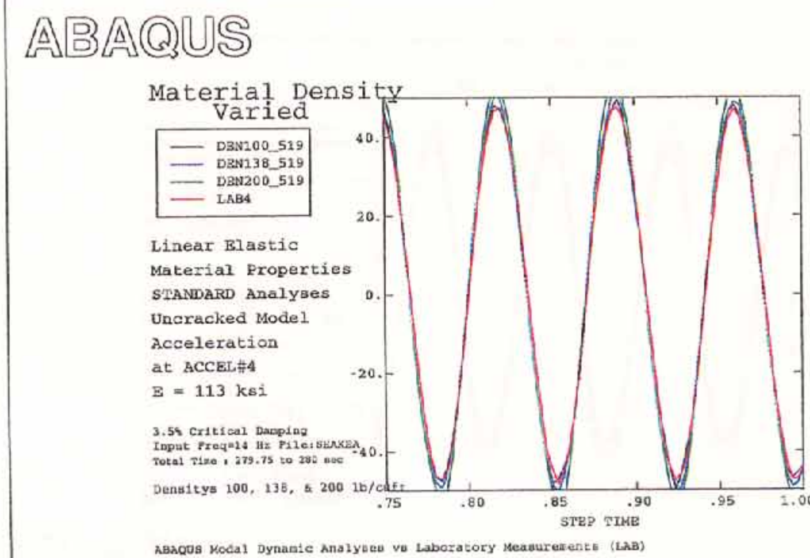
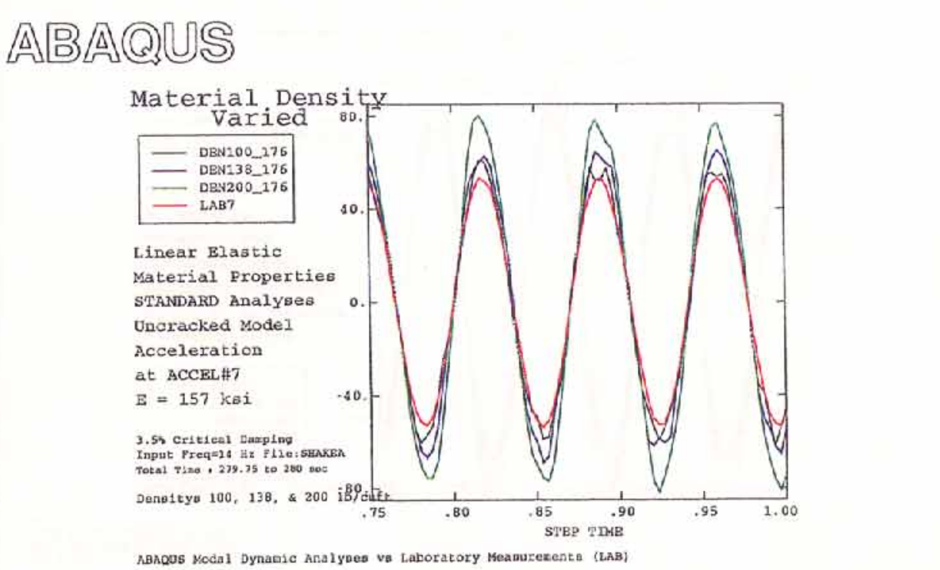
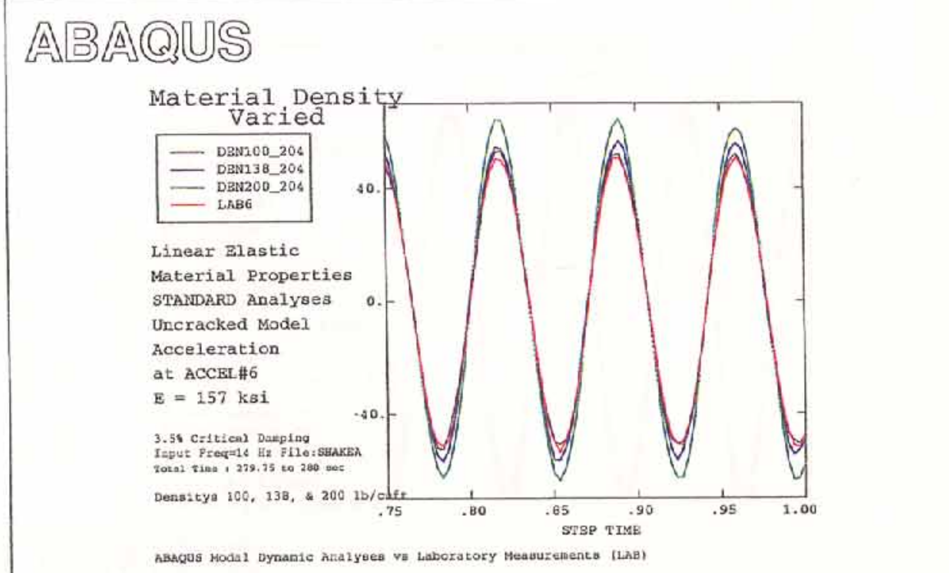
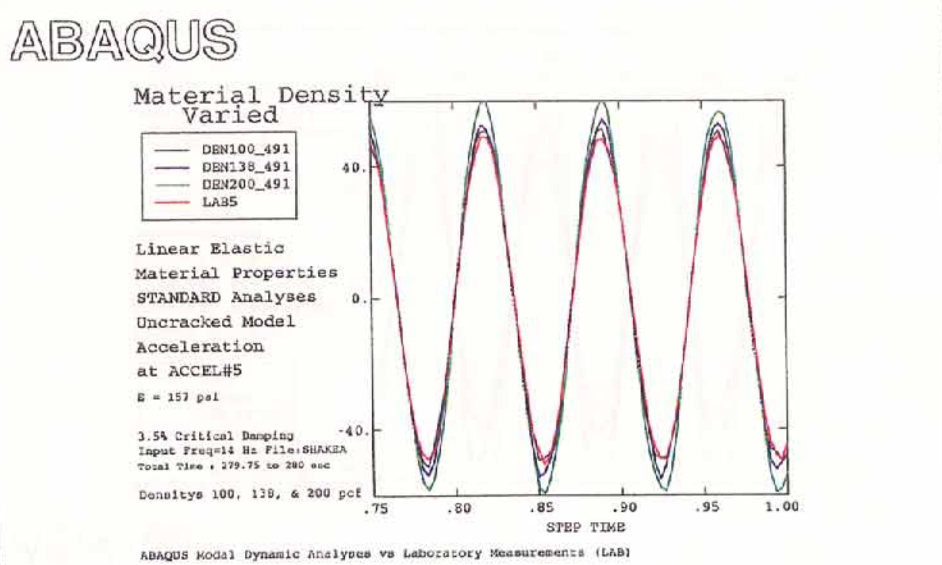

ABAQUS
Material Density Varied
DEN100_519
DEN138_519
DEN200_519
LAB4
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
E = 113 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
20.
0.
-20.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

Figure 947


ABAQUS
Material Density Varied
DBN100_176
DBN138_176
DBN200_176
LAB7
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
E = 157 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
80.
40.
0.
-40.
-80.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)


ABAQUS
Material Density Varied
DBN100_204
DBN138_204
DBN200_204
LAB6
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
E = 157 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)


ABAQUS
Material Density Varied
DBN100_491
DBN138_491
DBN200_491
LAB5
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
E = 157 psi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 pcf
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

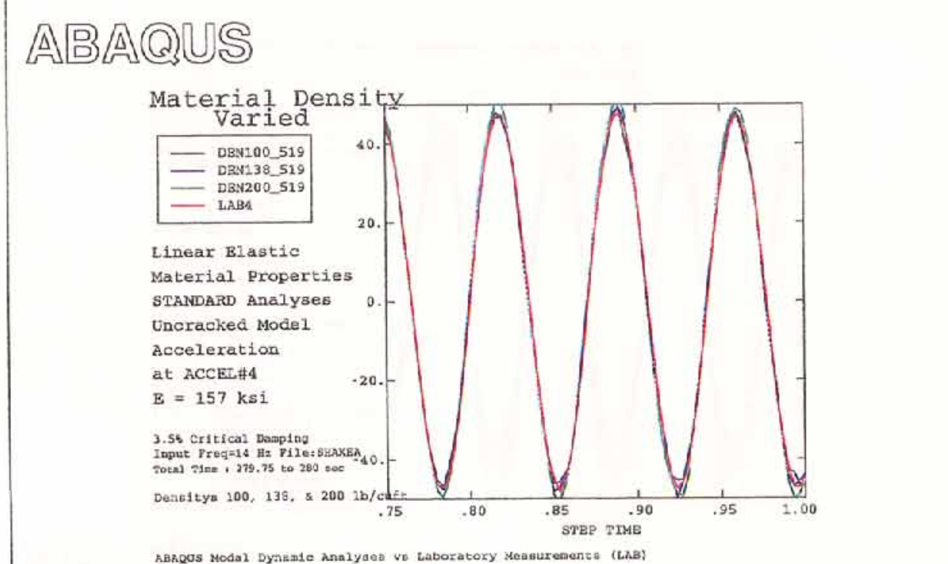

ABAQUS
Material Density Varied
DBN100_519
DBN138_519
DBN200_519
LAB4
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
E = 157 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
20.
0.
-20.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

Figure 948

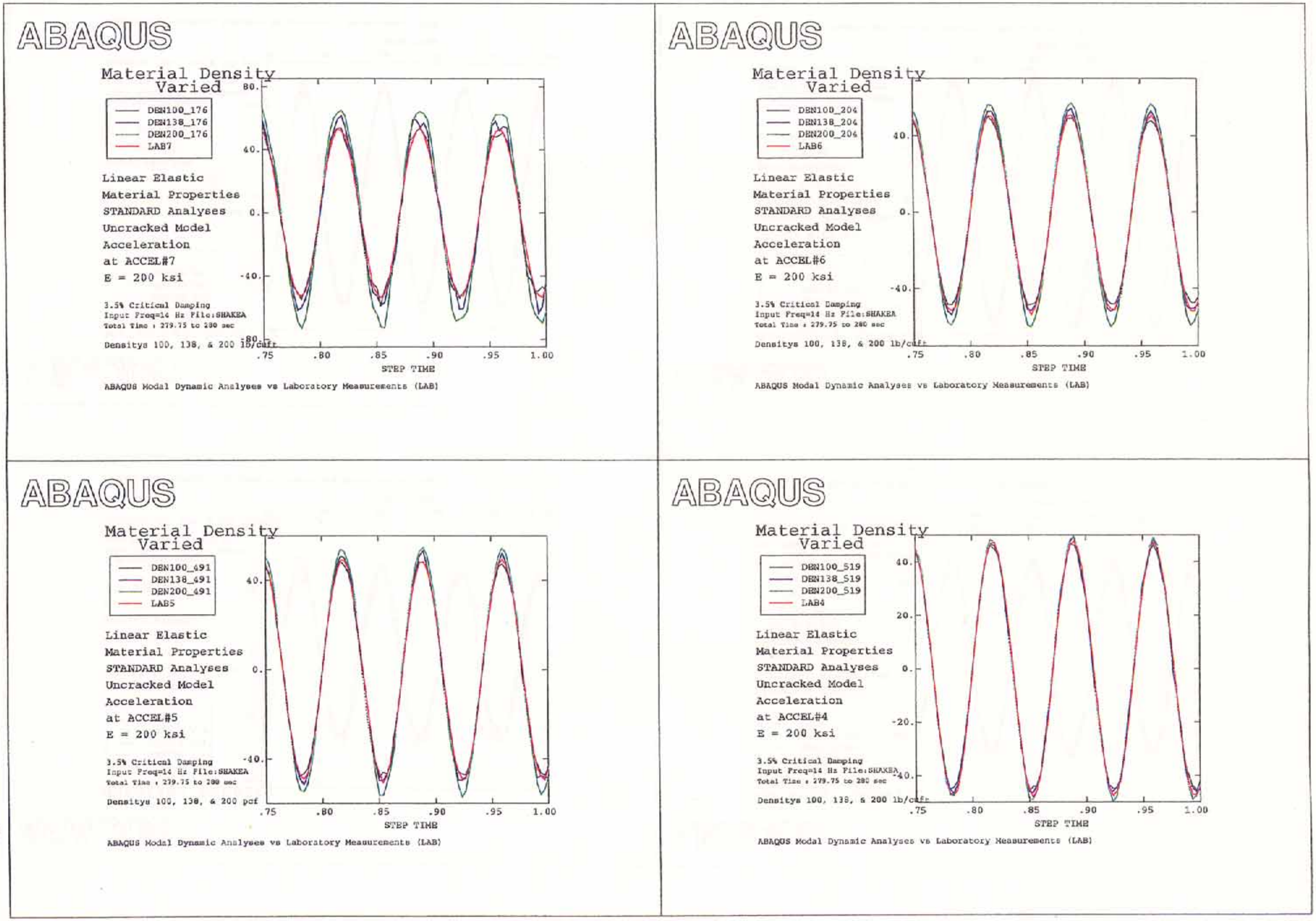
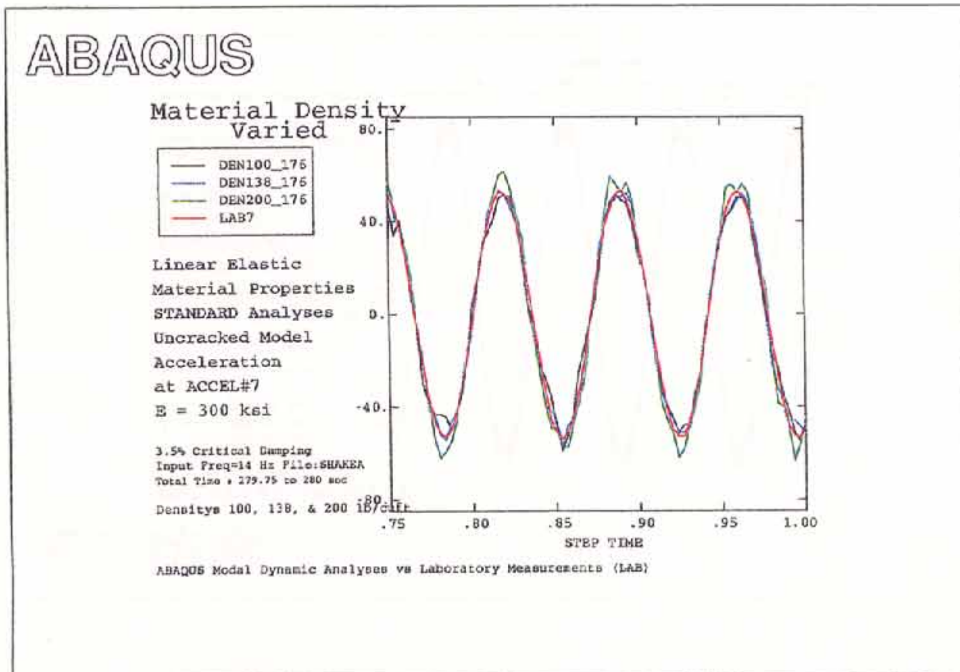
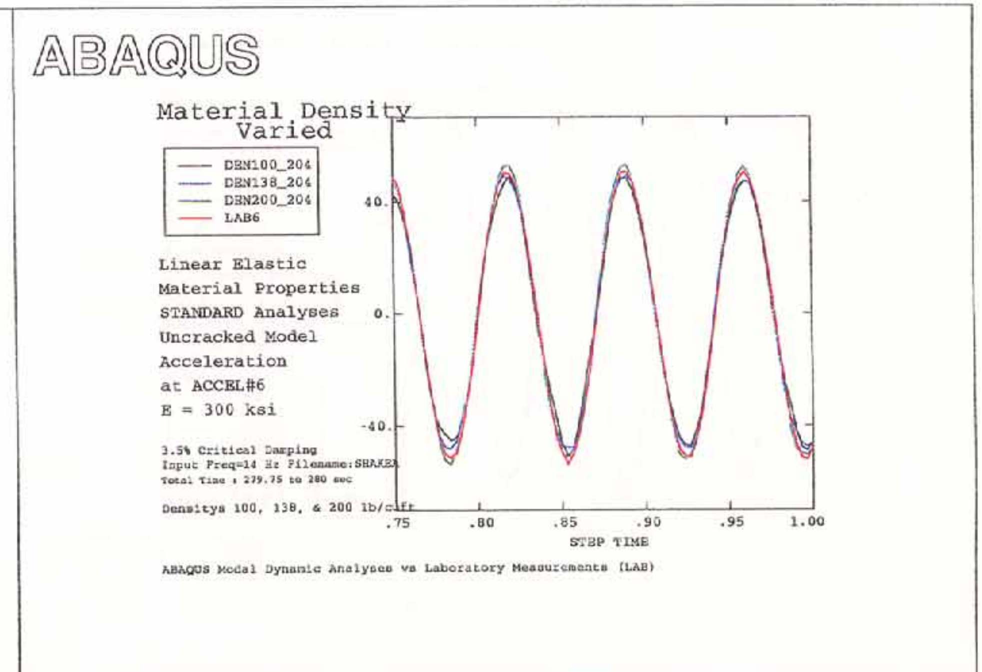
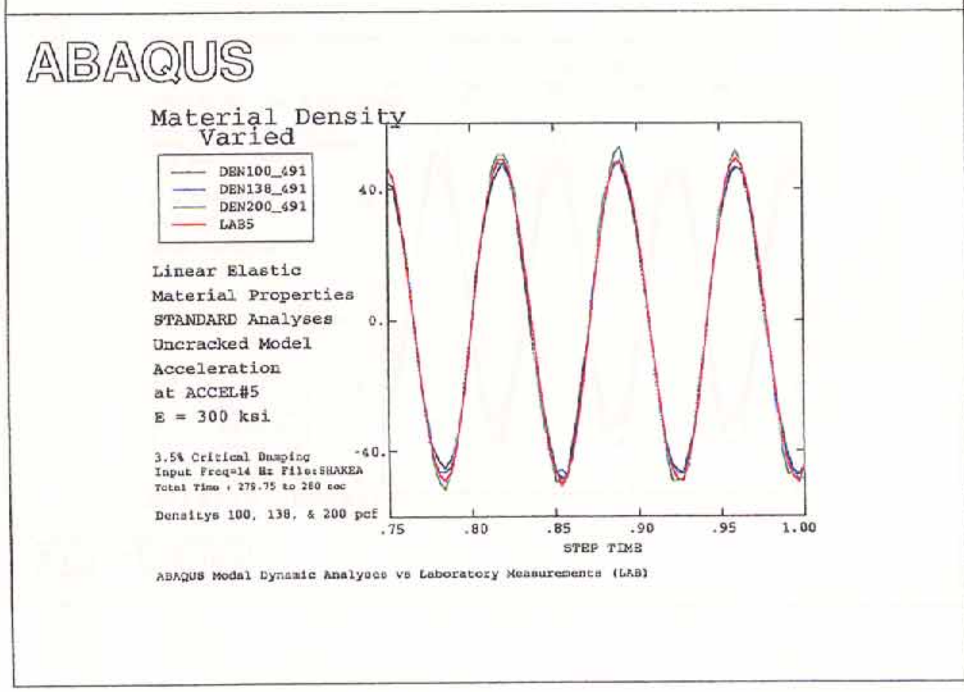

ABAQUS
Material Density Varied
DEN100_176
DEN138_176
DEN200_176
LAB7
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
E = 200 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
80.
40.
0.
-40.
-80.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)
ABAQUS
Material Density Varied
DEN100_204
DEN138_204
DEN200_204
LAB6
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
E = 200 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)
ABAQUS
Material Density Varied
DEN100_491
DEN138_491
DEN200_491
LAB5
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
E = 200 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 pcf
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)
ABAQUS
Material Density Varied
DEN100_519
DEN138_519
DEN200_519
LAB4
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
E = 200 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
20.
0.
-20.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

Figure 949


ABAQUS
Material Density Varied
DEN100_176
DEN138_176
DEN200_176
LAB7
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
E = 300 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
80.
40.
0.
-40.
-80.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)


ABAQUS
Material Density Varied
DEN100_204
DEN138_204
DEN200_204
LAB6
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
E = 300 ksi
3.5% Critical Damping
Input Freq=14 Hz Filename:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)


ABAQUS
Material Density Varied
DEN100_491
DEN138_491
DEN200_491
LAB5
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
E = 300 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 pcf
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

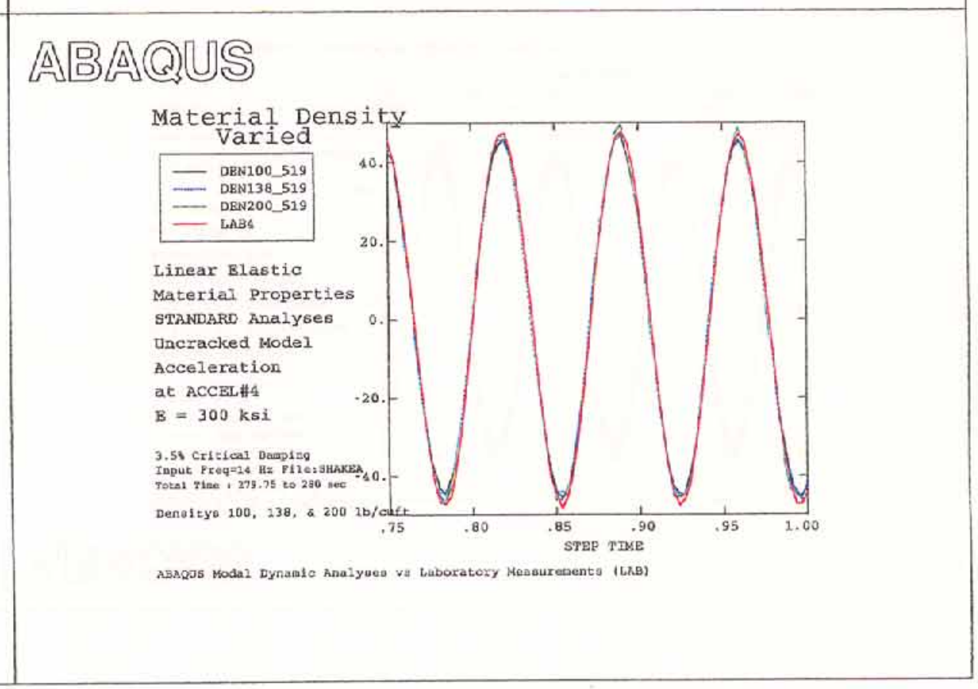
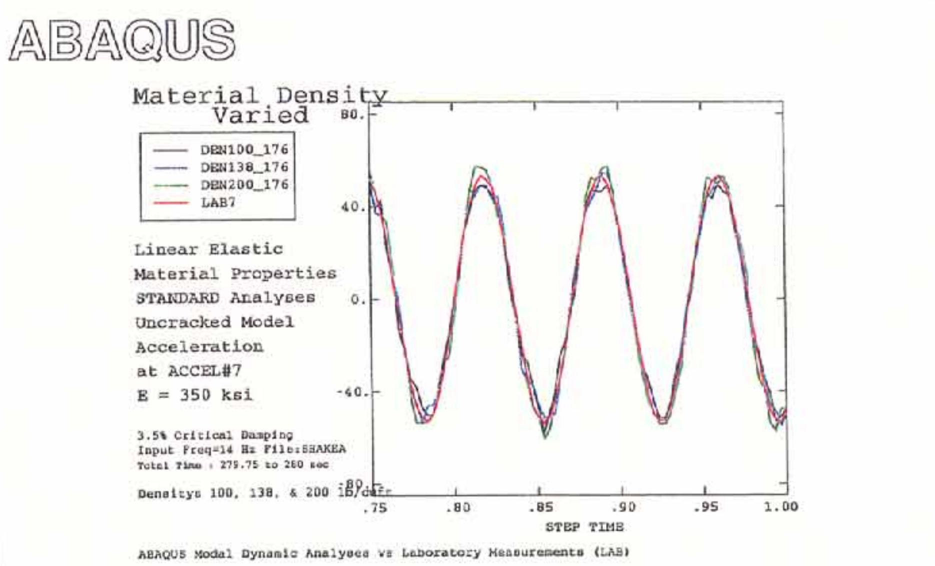
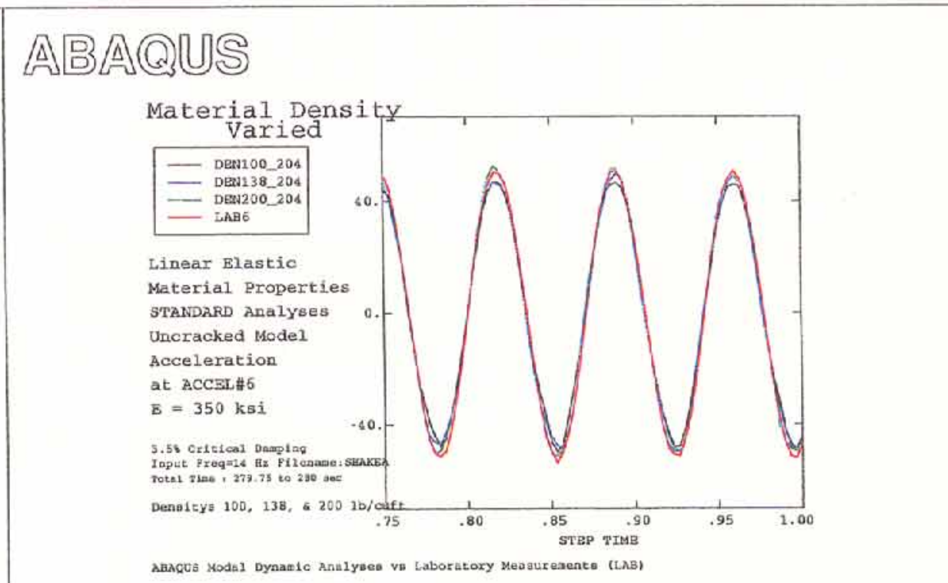
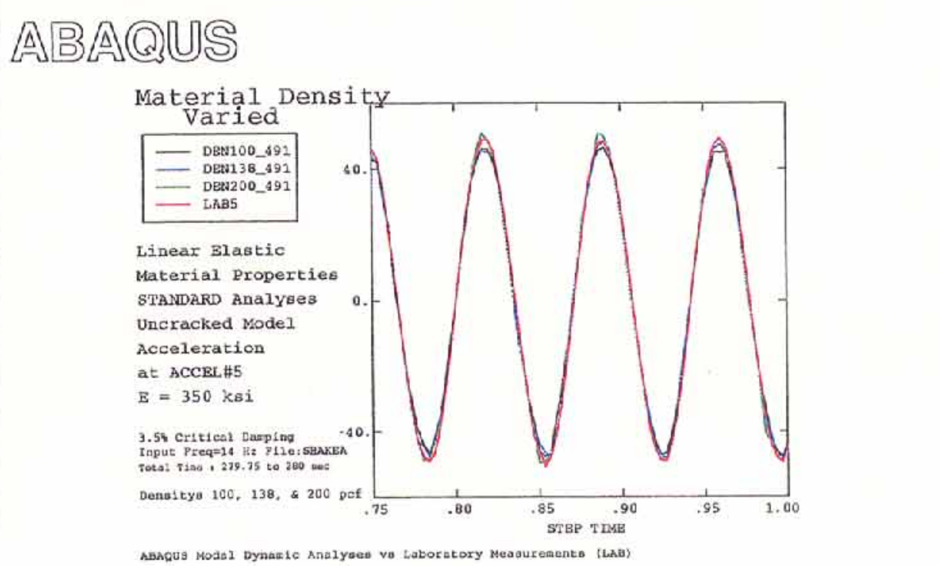

ABAQUS
Material Density Varied
DEN100_519
DEN138_519
DEN200_519
LAB4
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
E = 300 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
20.
0.
-20.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

Figure 950


ABAQUS
Material Density Varied
DEN100_176
DEN138_176
DEN200_176
LAB7
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
E = 350 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 275.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
80.
40.
0.
-40.
-80.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)


ABAQUS
Material Density Varied
DEN100_204
DEN138_204
DEN200_204
LAB6
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
E = 350 ksi
3.5% Critical Damping
Input Freq=14 Hz Filename:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)


ABAQUS
Material Density Varied
DEN100_491
DEN138_491
DEN200_491
LAB5
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
E = 350 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 pcf
40.
0.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

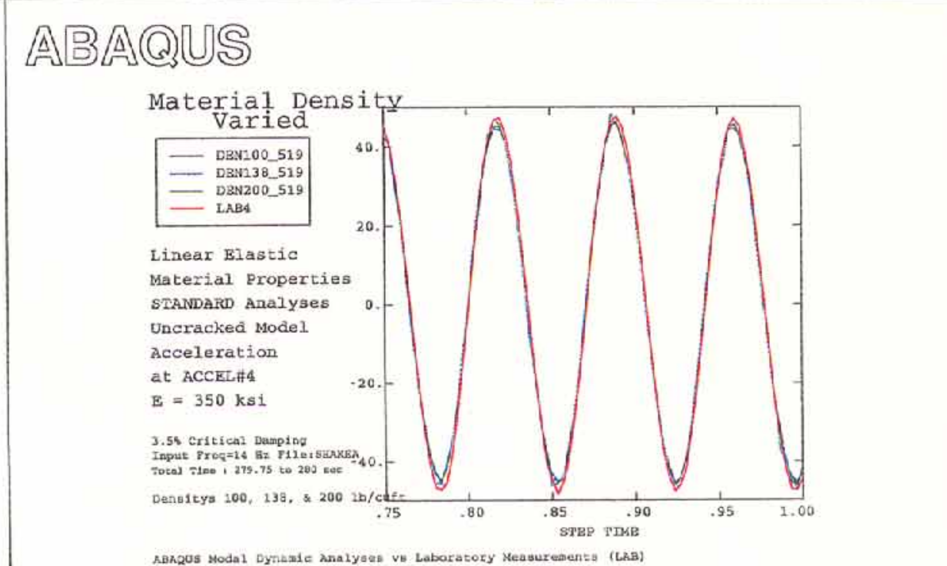
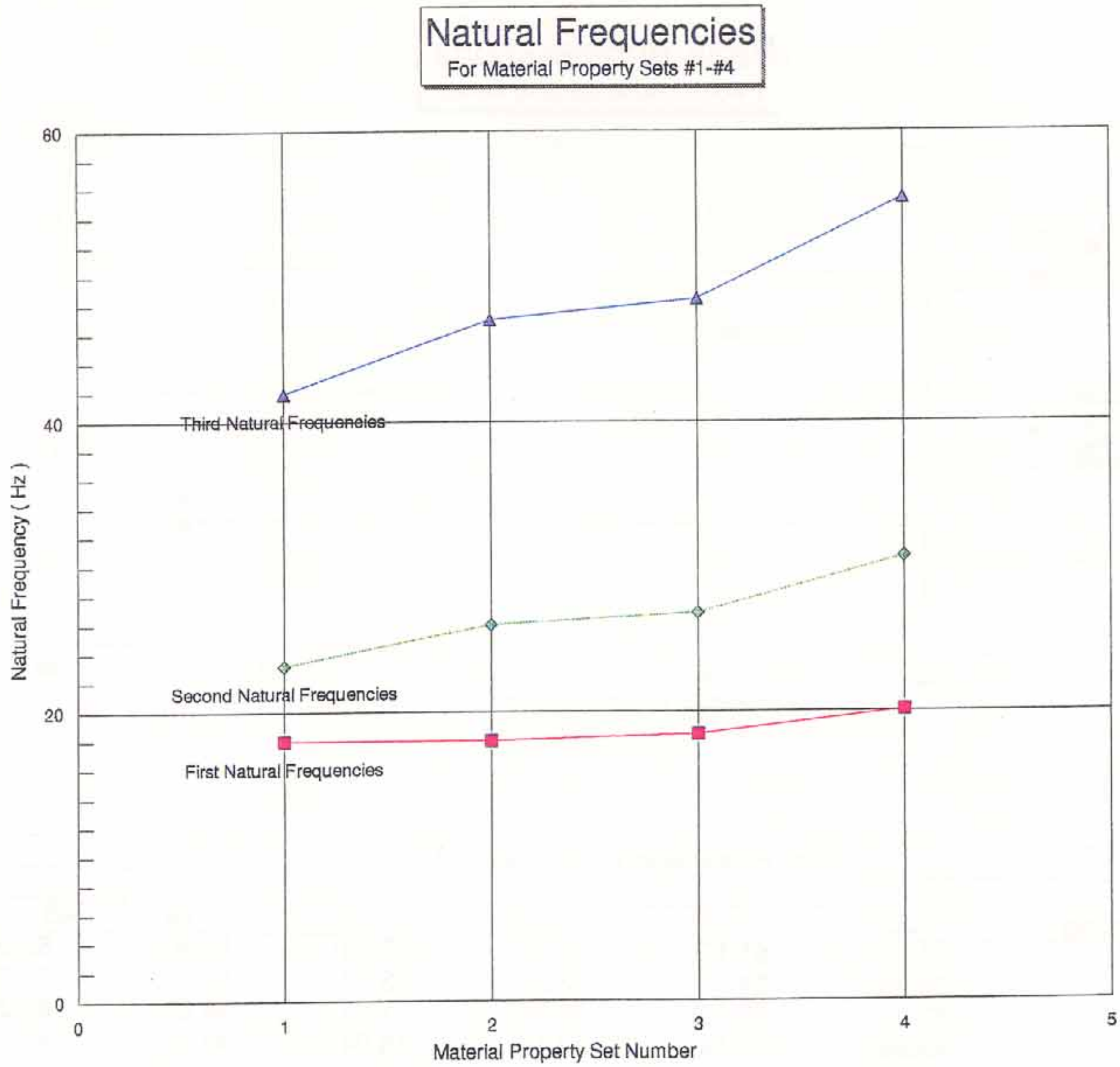

ABAQUS
Material Density Varied
DEN100_519
DEN138_519
DEN200_519
LAB4
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
E = 350 ksi
3.5% Critical Damping
Input Freq=14 Hz File:SHAKEA
Total Time : 279.75 to 280 sec
Densitys 100, 138, & 200 lb/cuft
40.
20.
0.
-20.
-40.
.75
.80
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements (LAB)

Figure g51

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3

Material Property Sets

Linear Elastic Material Property Set #1 : Elastic Modulus = 190 ksi; Material Density = 133 pcf
Linear Elastic Material Property Set #2 : Elastic Modulus = 200 ksi; Material Density = 140 pcf
Linear Elastic Material Property Set #3 : Elastic Modulus = 210 ksi; Material Density = 140 pcf
Linear Elastic Material Property Set #4 : Elastic Modulus = 250 ksi; Material Density = 140 pcf



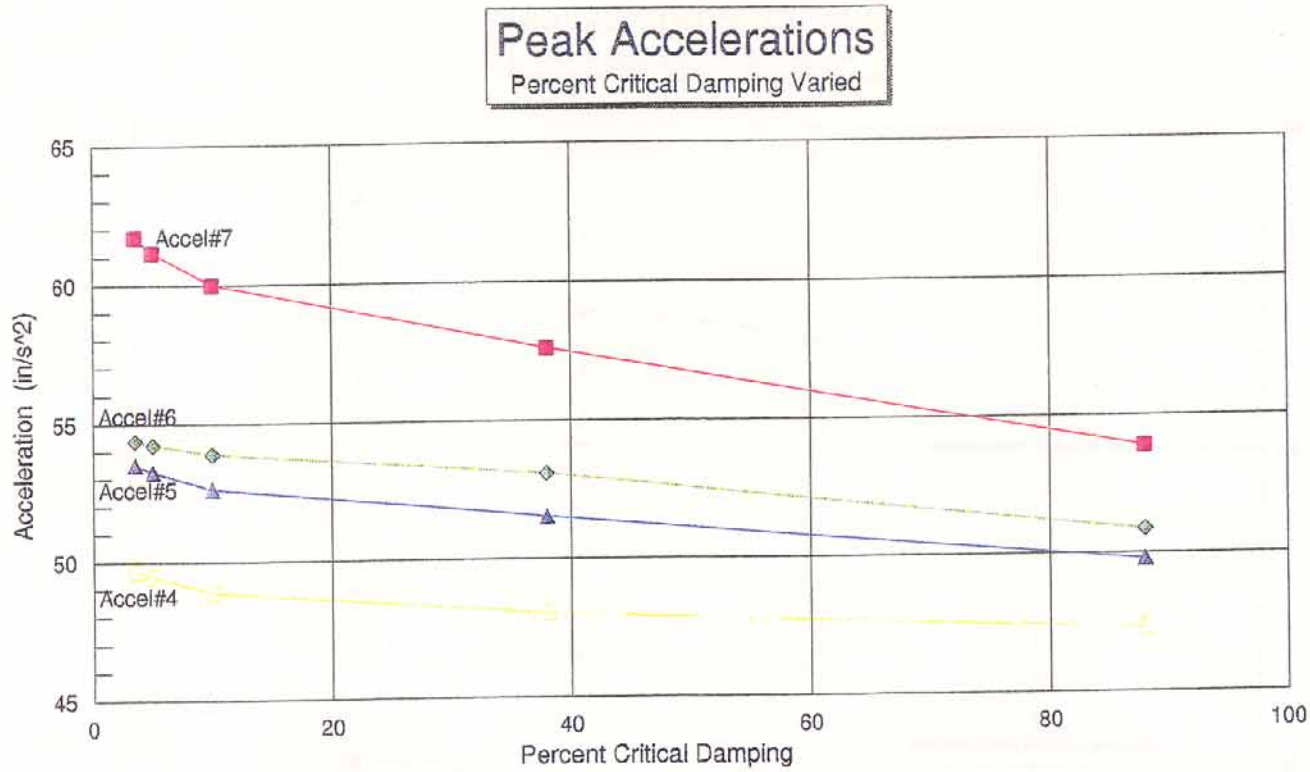
Natural Frequencies (Hz)

Material Property Set #	1	2	3	4	LAB
Mode					
1	18.0	18.0	18.4	20.1	18.0
2	23.2	26.0	26.8	30.6	24.0
3	41.9	47.0	48.4	55.4	30.0

Figure h1

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%, 5%, 10%, 38% & 88%) critical

Linear Elastic Material Property Set #1 : Elastic Modulus = 190 ksi; Material Density = 133 pcf

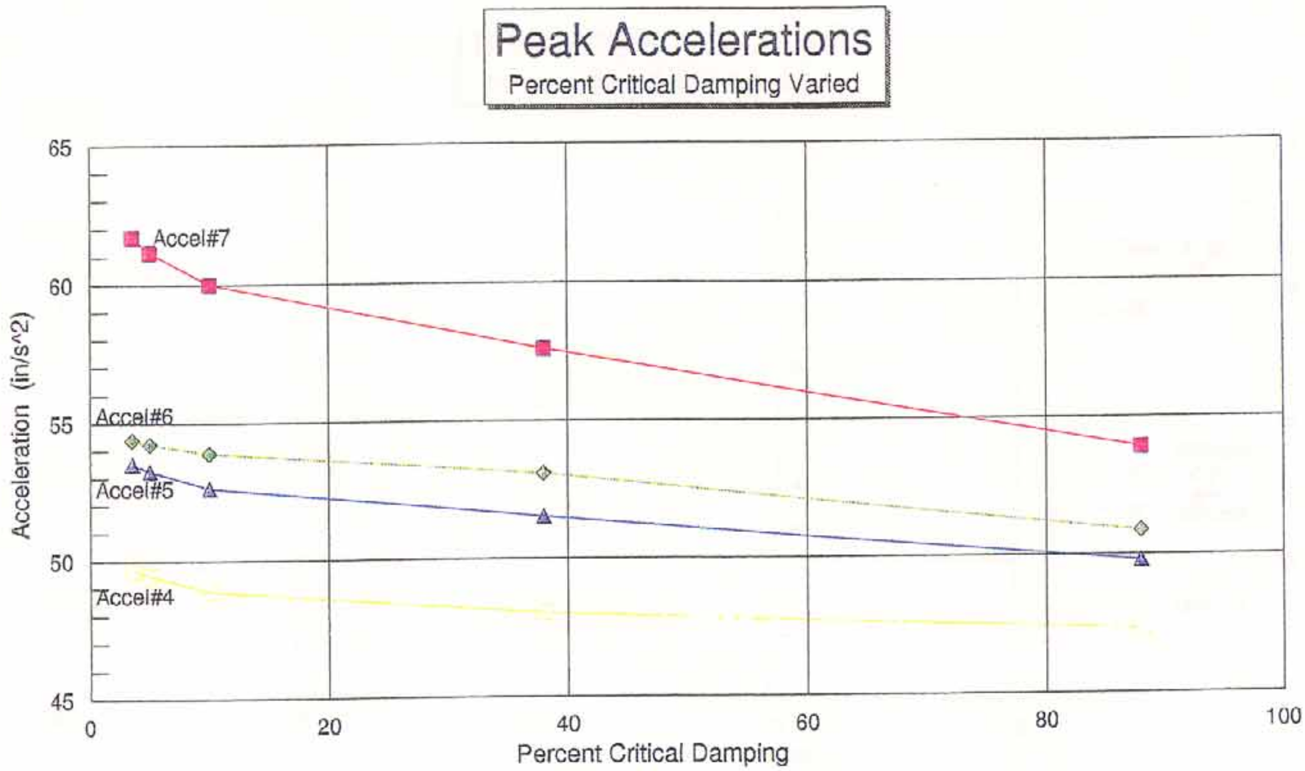


Peak Accelerations (inch / sec ^ 2)						
Percent Damping	3.5	5	10	38	88	LAB
Accel#7	61.73	61.17	59.99	57.60	53.90	53.26
Accel#6	54.39	54.23	53.88	53.07	50.87	51.72
Accel#5	53.52	53.25	52.61	51.53	49.80	49.26
Accel#4	49.66	49.44	48.87	48.04	47.32	47.72
CPU seconds	278.83	278.65	278.89	268.59	267.18	

Figure h2

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%, 5%, 10%, 38%, & 88%) critical

Linear Elastic Material Property Set #2 : Elastic Modulus = 200 ksi; Material Density = 140 pcf



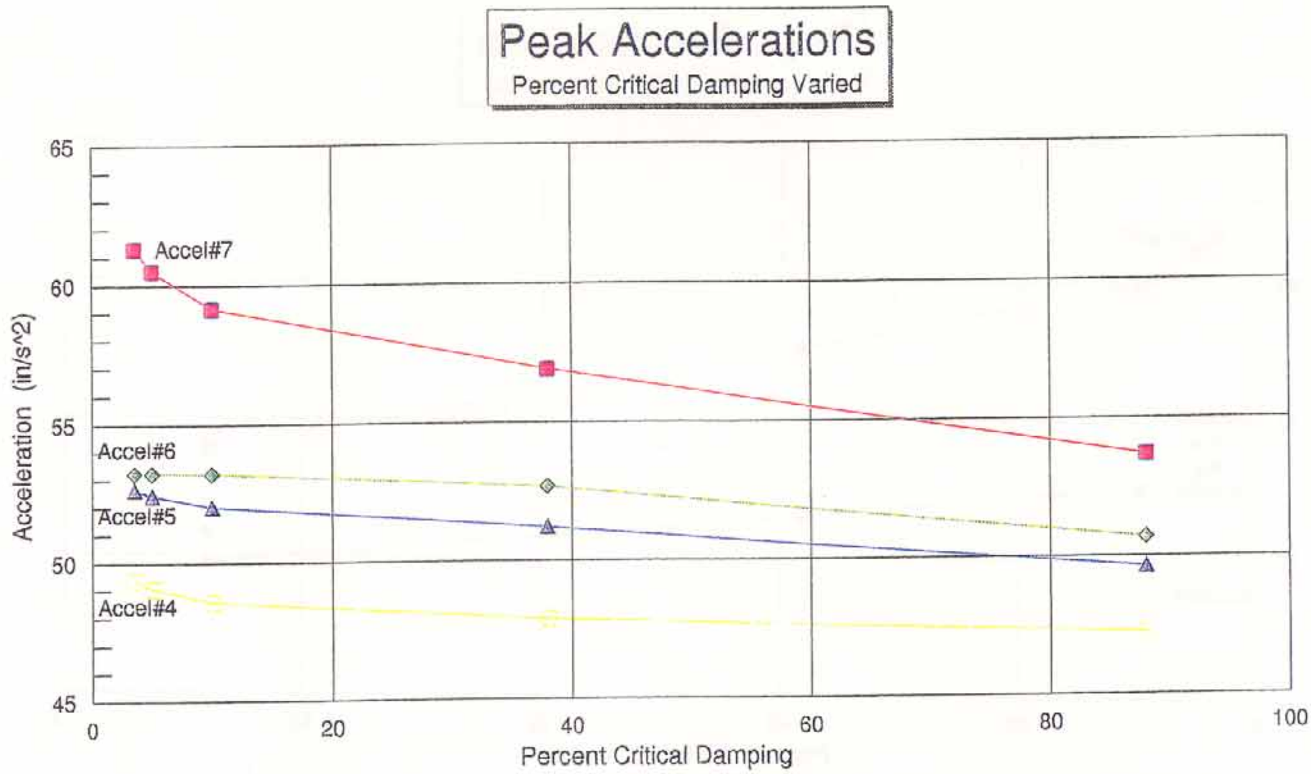
Peak Accelerations (inch / sec ^ 2)

Percent Damping	3.5	5	10	38	88	LAB
Accel#7	61.73	61.17	59.99	57.60	53.90	53.26
Accel#6	54.39	54.23	53.88	53.07	50.87	51.72
Accel#5	53.52	53.25	52.61	51.53	49.80	49.26
Accel#4	49.66	49.44	48.87	48.04	47.34	47.72

Figure h3

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%,5%,10%,38%,&88%) critical

Linear Elastic Material Property Set #3 : Elastic Modulus = 210 ksi; Material Density = 140 pcf



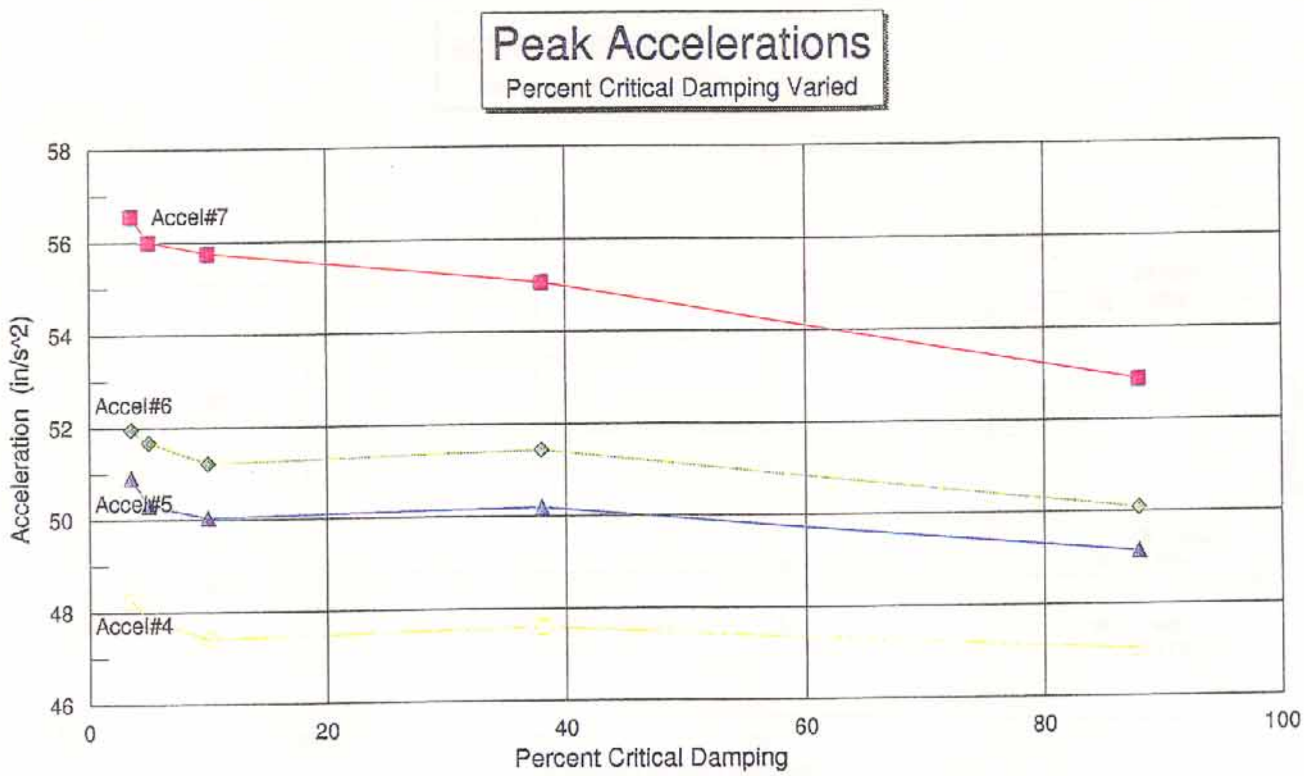
Peak Accelerations (inch / sec ^ 2)

Percent Damping	3.5	5	10	38	88	LAB
Accel#7	61.31	60.51	59.15	56.91	53.68	53.26
Accel#6	53.22	53.23	53.21	52.67	50.70	51.72
Accel#5	52.65	52.43	52.02	51.21	49.65	49.26
Accel#4	49.36	49.06	48.57	47.90	47.27	47.72

Figure h4

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%, 5%, 10%, 38% & 88%) critical

Linear Elastic Material Property Set #4 : Elastic Modulus = 250 ksi; Material Density = 140 pcf



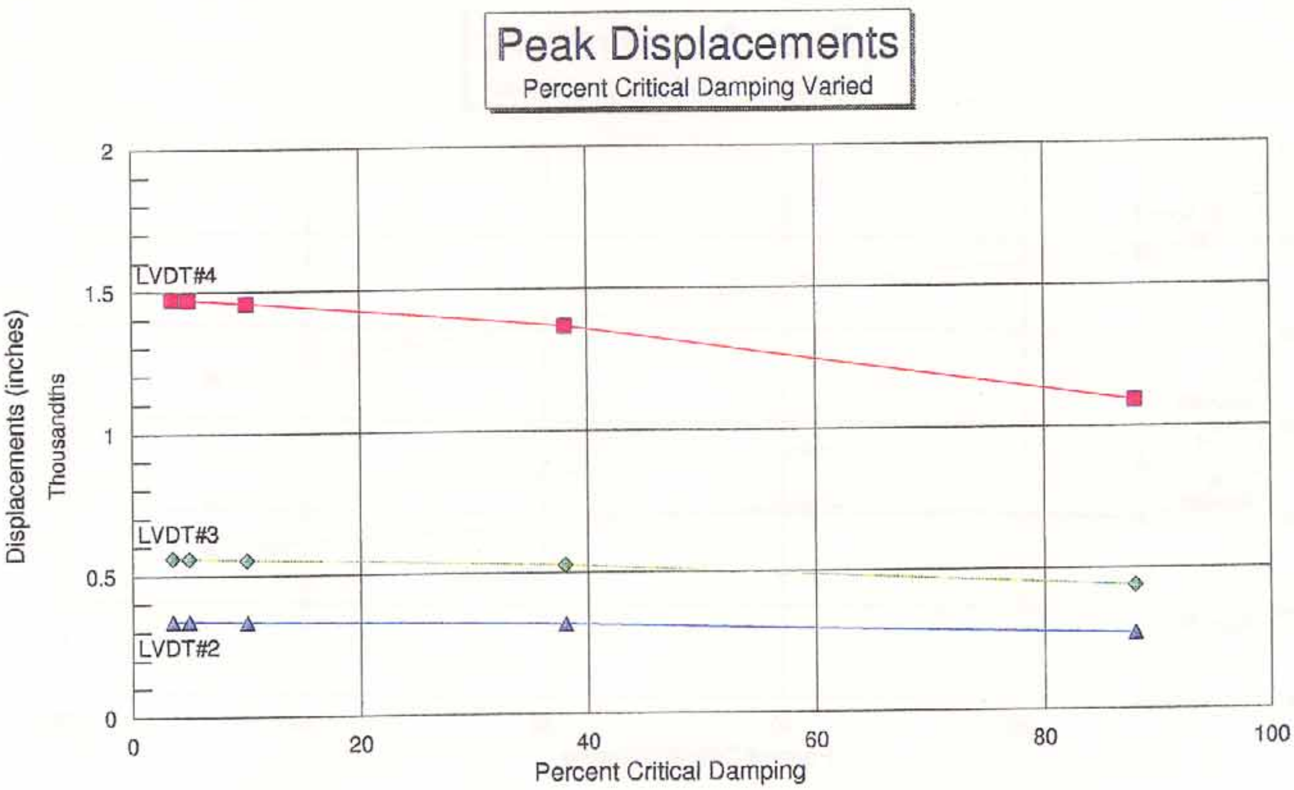
Peak Accelerations (inch / sec ^ 2)

Percent Damping	3.5	5	10	38	88	LAB
Accel#7	56.56	56.01	55.76	55.07	52.87	53.26
Accel#6	51.95	51.67	51.22	51.43	50.09	51.72
Accel#5	50.90	50.30	50.04	50.19	49.14	49.26
Accel#4	48.26	47.84	47.41	47.60	47.03	47.72

Figure h5

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%,5%,10%,38%,&88%) critical

Linear Elastic Material Property Set #1 : Elastic Modulus = 190 ksi; Material Density = 133 pcf

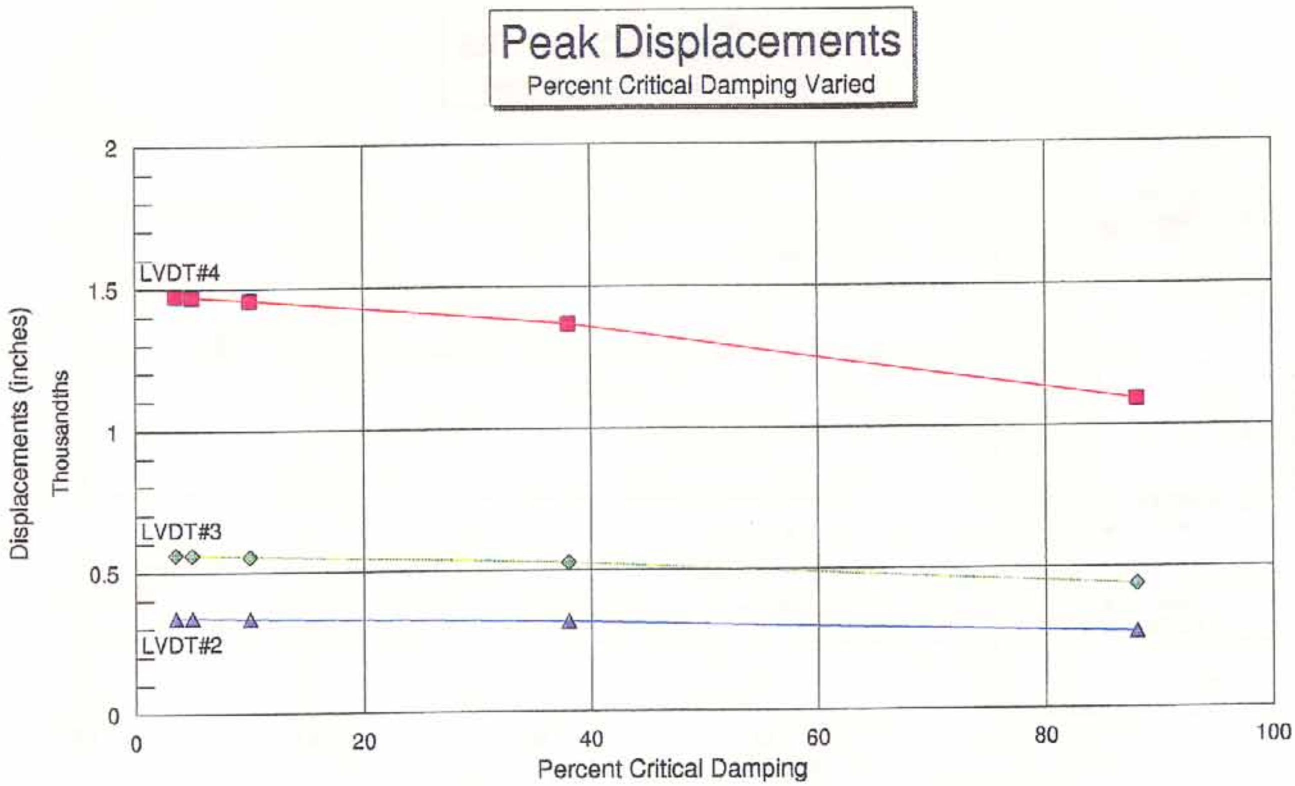


Peak Displacements (inches)						
Percent Damping	3.5	5	10	38	88	LAB
LVDT#4 LVDT#3 LVDT#2	1.5E-03 5.6E-04 3.4E-04	1.5E-03 5.6E-04 3.4E-04	1.5E-03 5.5E-04 3.3E-04	1.4E-03 5.3E-04 3.2E-04	1.1E-03 4.4E-04 2.7E-04	7.8E-04 3.0E-04 1.8E-04
CPU seconds	278.83	278.65	278.89	268.59	267.18	

Figure h6

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%,5%,10%,38%,&88%) critical

Linear Elastic Material Property Set #2 : Elastic Modulus = 200 ksi; Material Density = 140 pcf

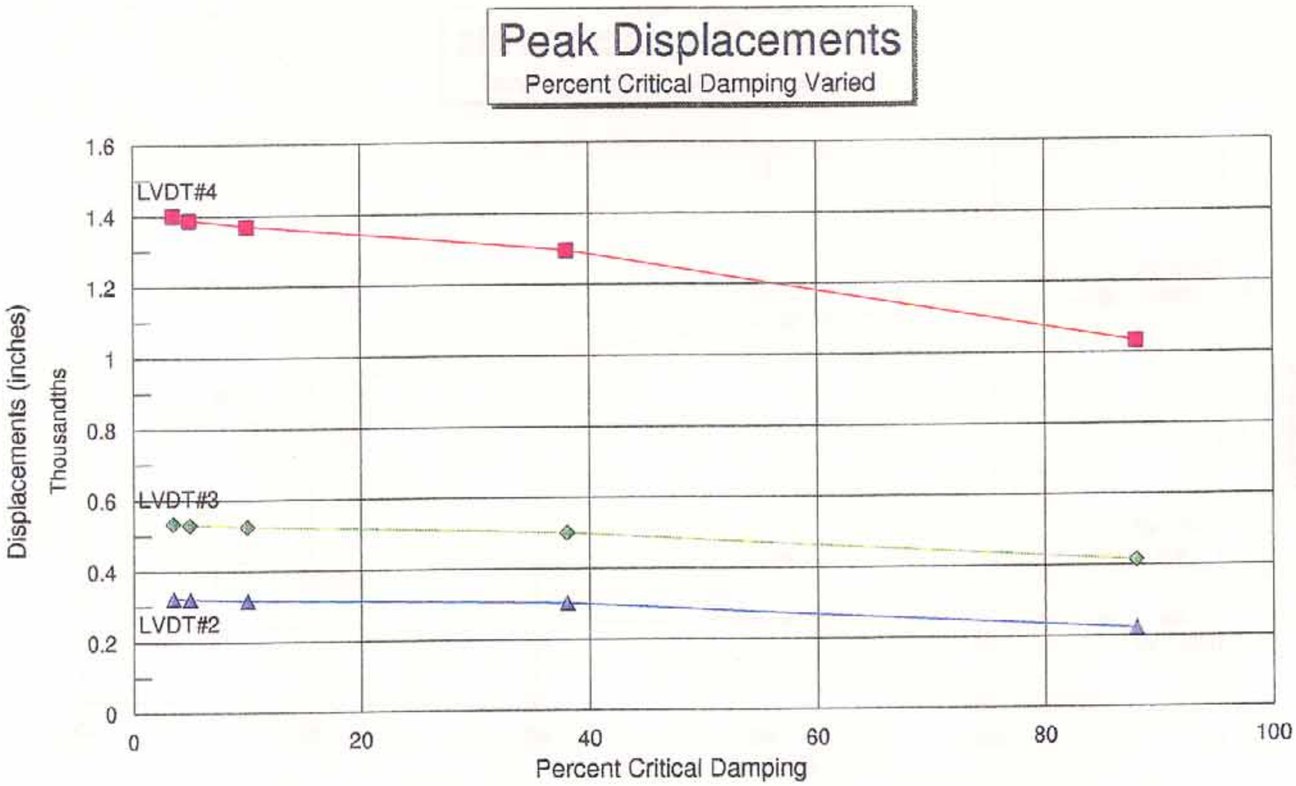


Peak Displacements (inches)						
Percent Damping	3.5	5	10	38	88	LAB
LVDT#4	1.5E-03	1.5E-03	1.5E-03	1.4E-03	1.1E-03	7.8E-04
LVDT#3	5.6E-04	5.6E-04	5.5E-04	5.3E-04	4.4E-04	3.0E-04
LVDT#2	3.4E-04	3.4E-04	3.3E-04	3.2E-04	2.7E-04	1.8E-04

Figure h7

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%,5%,10%,38%,&88%) critical

Linear Elastic Material Property Set #3 : Elastic Modulus = 210 ksi; Material Density = 140 pcf



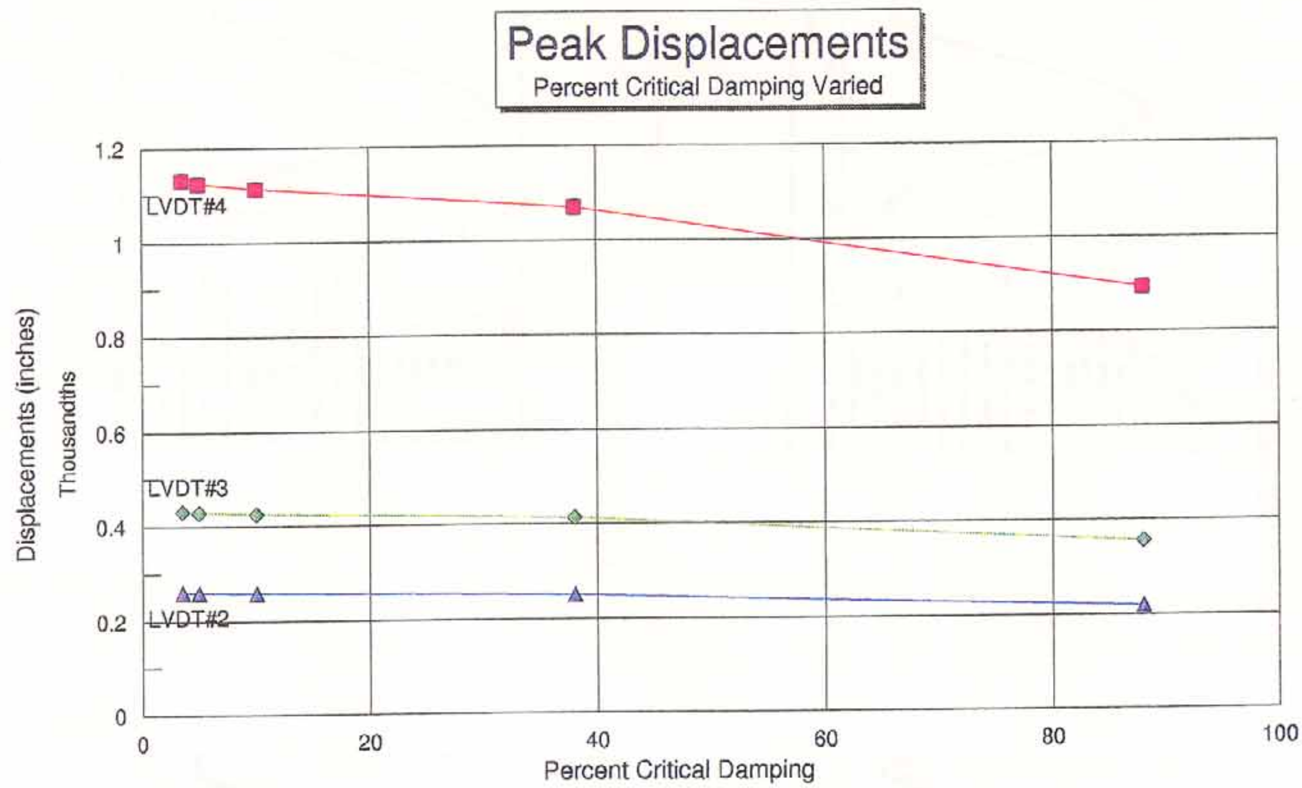
Peak Displacements (inches)

Percent Damping	3.5	5	10	38	88	LAB
LVDT#4	1.4E-03	1.4E-03	1.4E-03	1.3E-03	1.0E-03	7.8E-04
LVDT#3	5.3E-04	5.3E-04	5.2E-04	5.0E-04	4.1E-04	3.0E-04
LVDT#2	3.2E-04	3.2E-04	3.2E-04	3.0E-04	2.2E-04	1.8E-04

Figure h8

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Percent Critical Damping
Mesh#3
Modal Damping = (3.5%,5%,10%,38%,&88%) critical

Linear Elastic Material Property Set #4 : Elastic Modulus = 250 ksi; Material Density = 140 pcf



Peak Displacements (inches)						
Percent Damping	3.5	5	10	38	88	LAB
LVDT#4	1.1E-03	1.1E-03	1.1E-03	1.1E-03	8.9E-04	7.8E-04
LVDT#3	4.3E-04	4.3E-04	4.3E-04	4.1E-04	3.6E-04	3.0E-04
LVDT#2	2.6E-04	2.6E-04	2.6E-04	2.5E-04	2.2E-04	1.8E-04

Figure h9

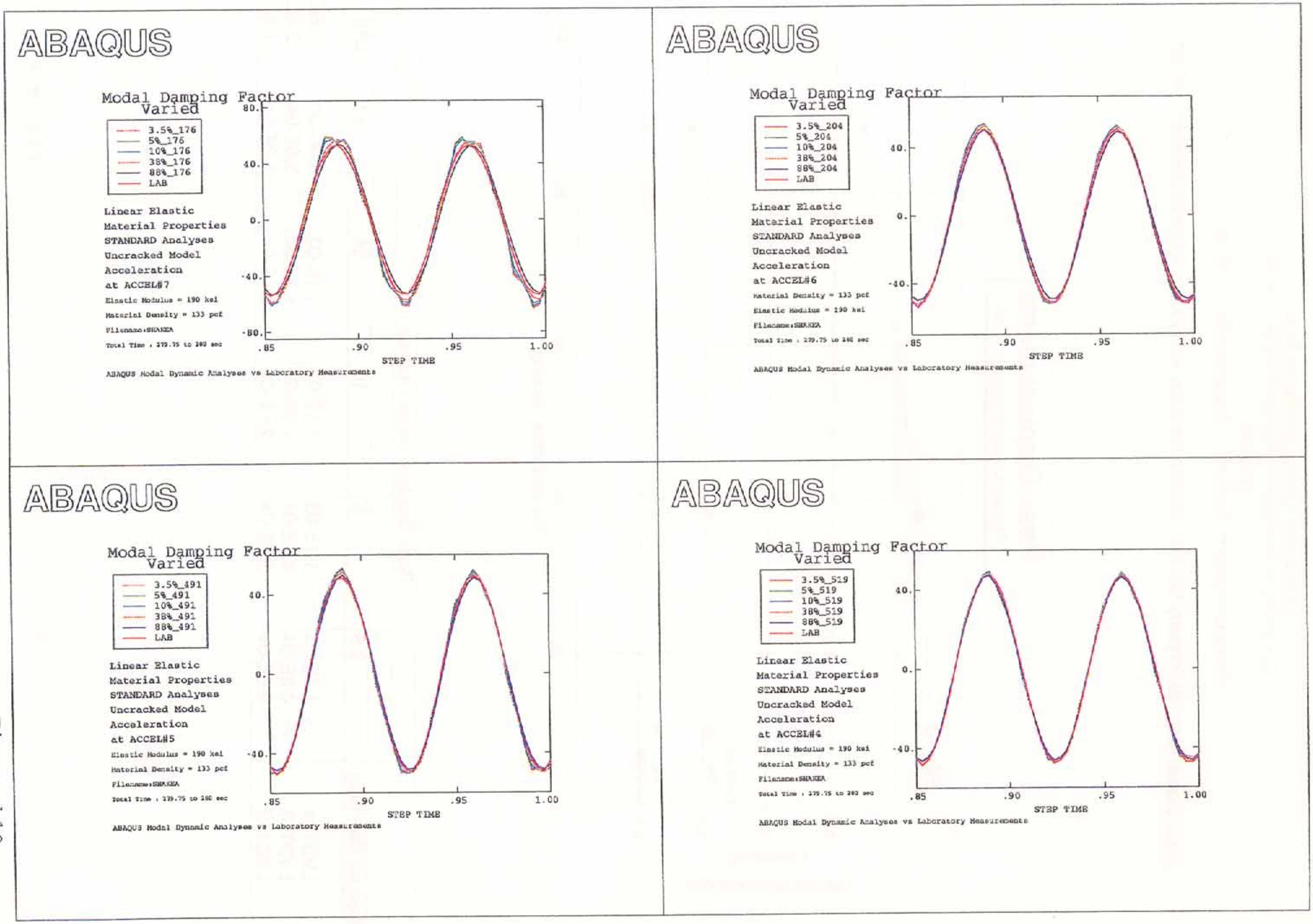
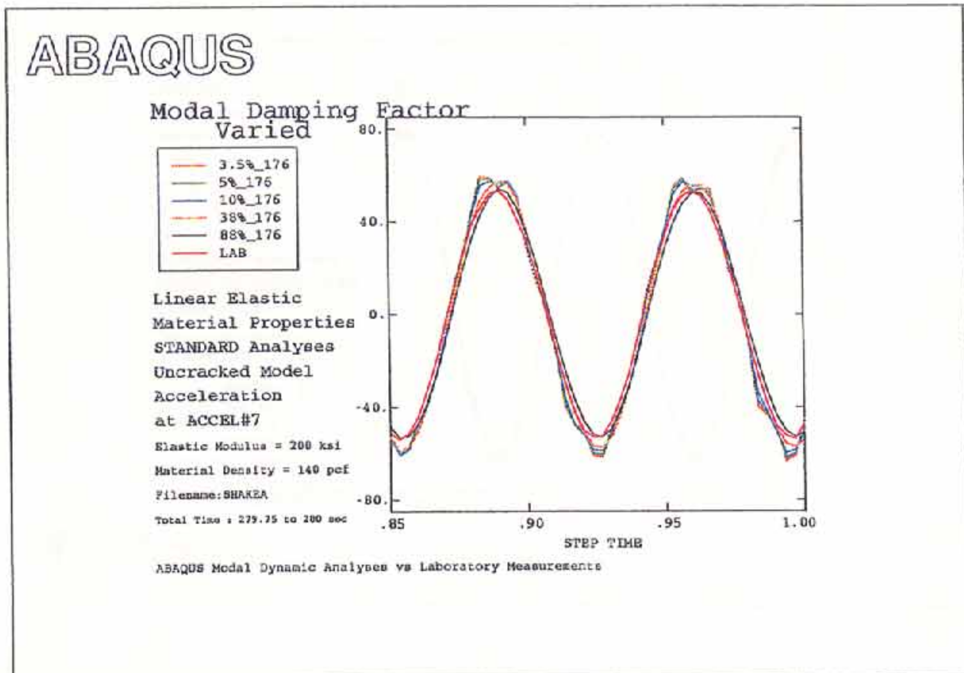
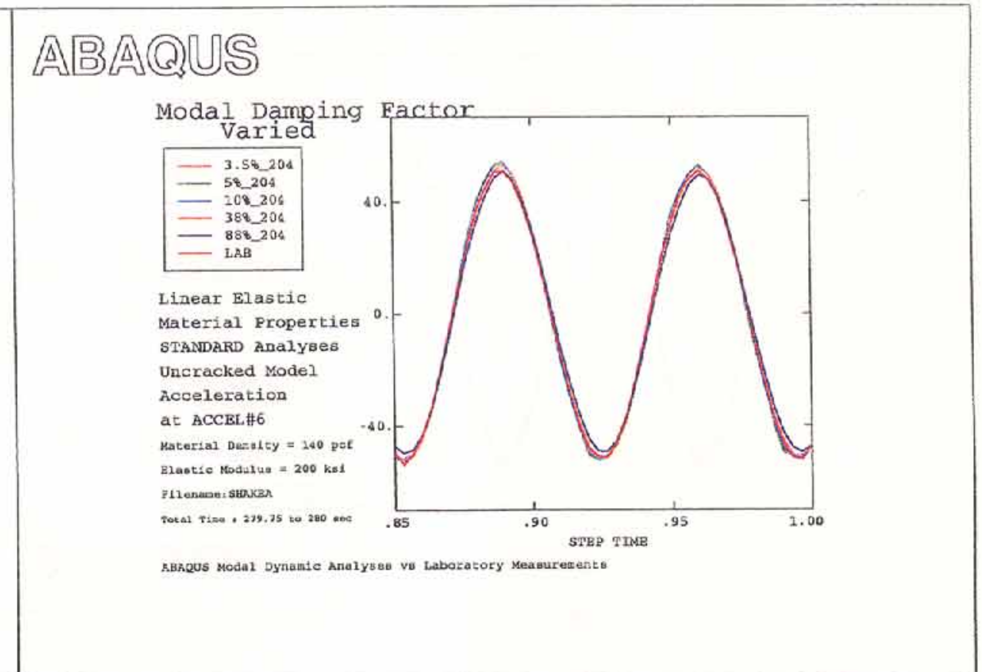

ABAQUS
Modal Damping Factor Varied
3.5%_176
5%_176
10%_176
38%_176
88%_176
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Elastic Modulus = 190 ksi
Material Density = 133 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements
ABAQUS
Modal Damping Factor Varied
3.5%_204
5%_204
10%_204
38%_204
88%_204
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Material Density = 133 pcf
Elastic Modulus = 190 ksi
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements
ABAQUS
Modal Damping Factor Varied
3.5%_491
5%_491
10%_491
38%_491
88%_491
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Elastic Modulus = 190 ksi
Material Density = 133 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements
ABAQUS
Modal Damping Factor Varied
3.5%_519
5%_519
10%_519
38%_519
88%_519
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Elastic Modulus = 190 ksi
Material Density = 133 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

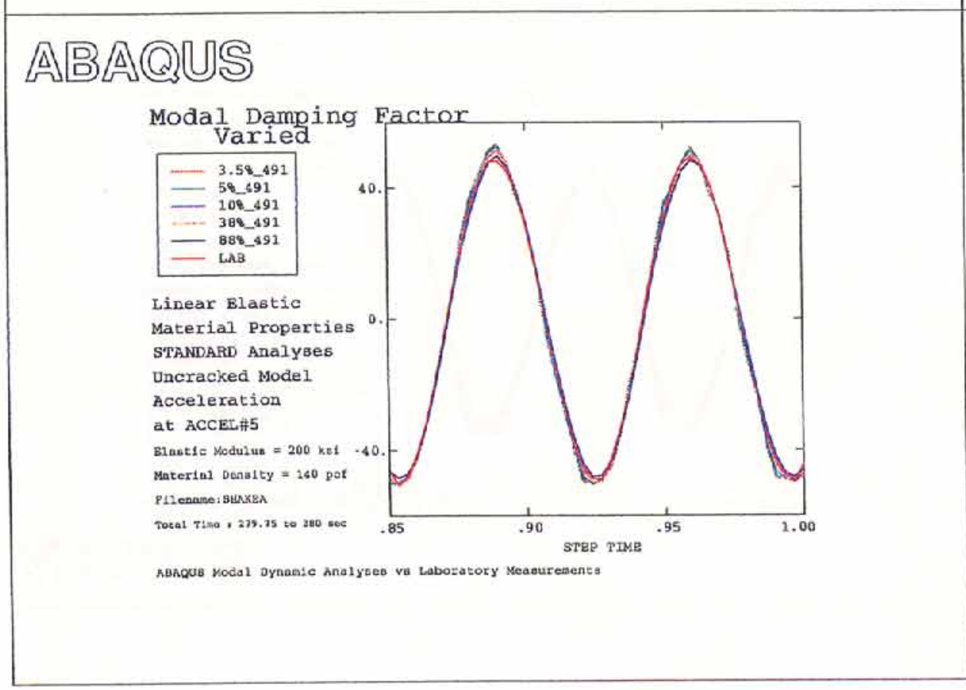
Figure h10



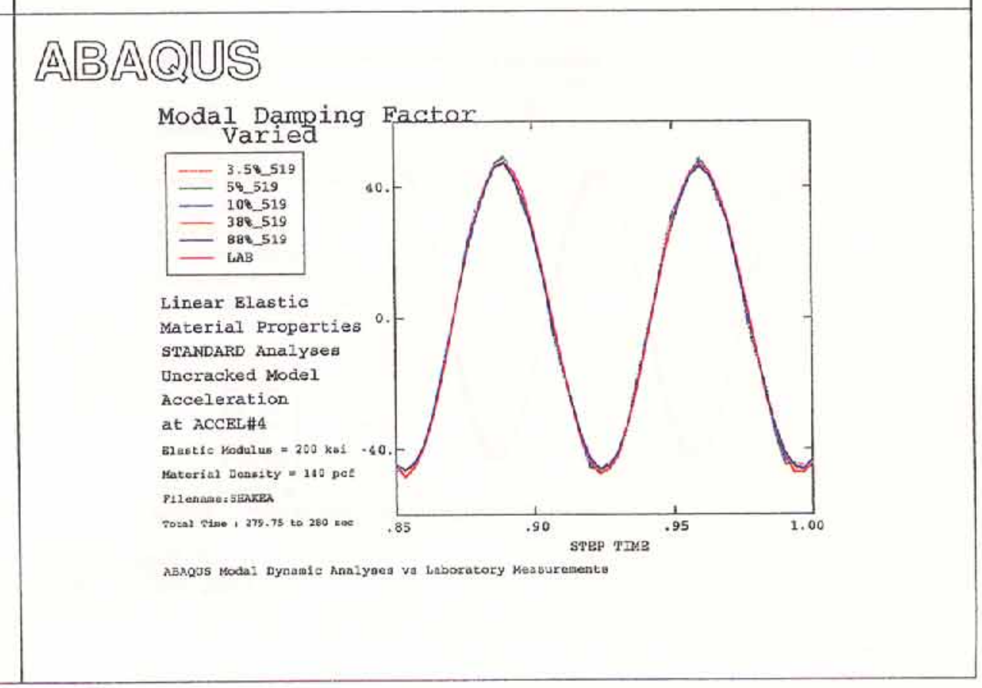
ABAQUS
Modal Damping Factor Varied
3.5%_176
5%_176
10%_176
38%_176
88%_176
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Elastic Modulus = 200 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements



ABAQUS
Modal Damping Factor Varied
3.5%_204
5%_204
10%_204
38%_204
88%_204
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Material Density = 140 pcf
Elastic Modulus = 200 ksi
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements



ABAQUS
Modal Damping Factor Varied
3.5%_491
5%_491
10%_491
38%_491
88%_491
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Elastic Modulus = 200 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements



ABAQUS
Modal Damping Factor Varied
3.5%_519
5%_519
10%_519
38%_519
88%_519
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Elastic Modulus = 200 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

Figure h11

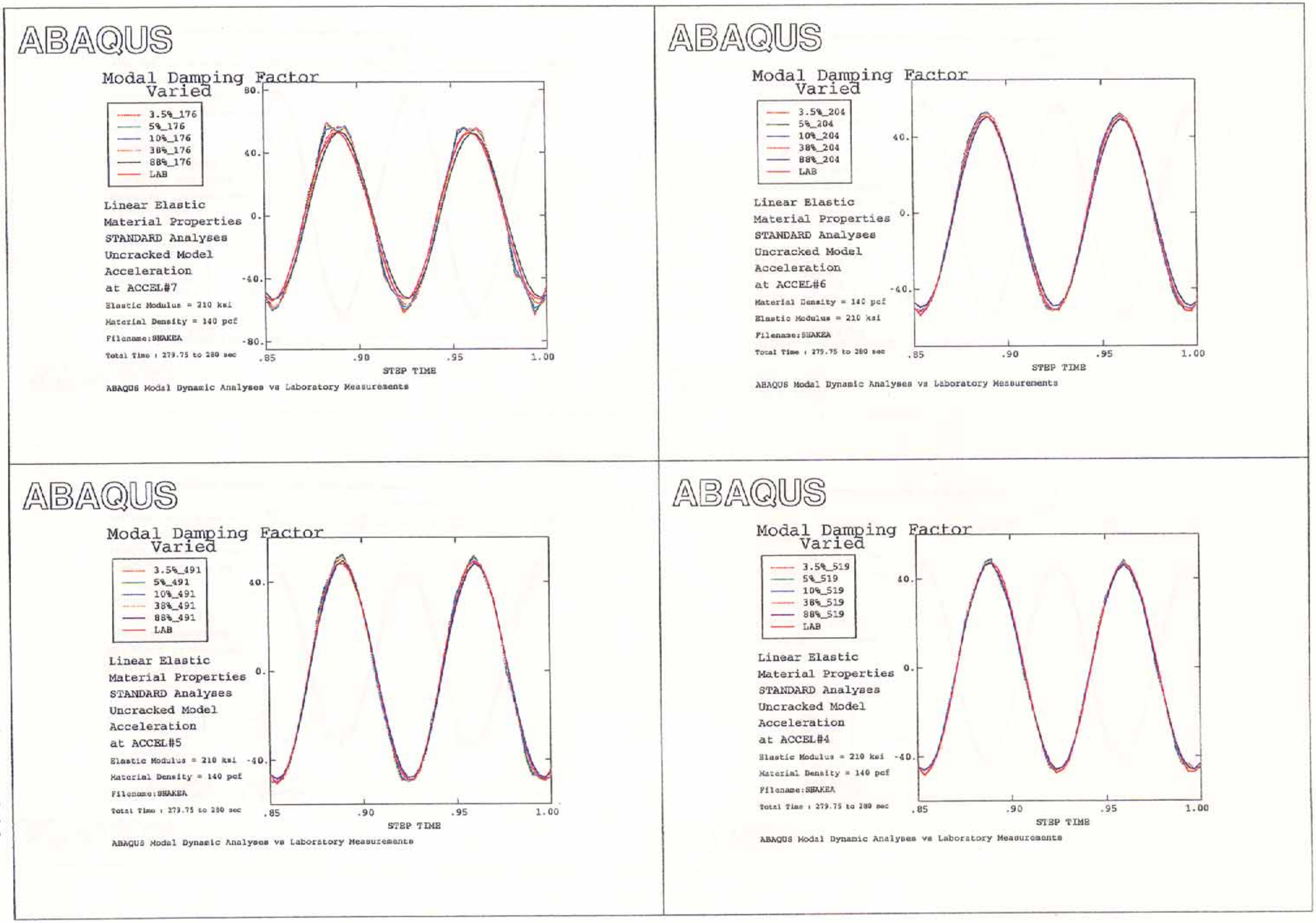
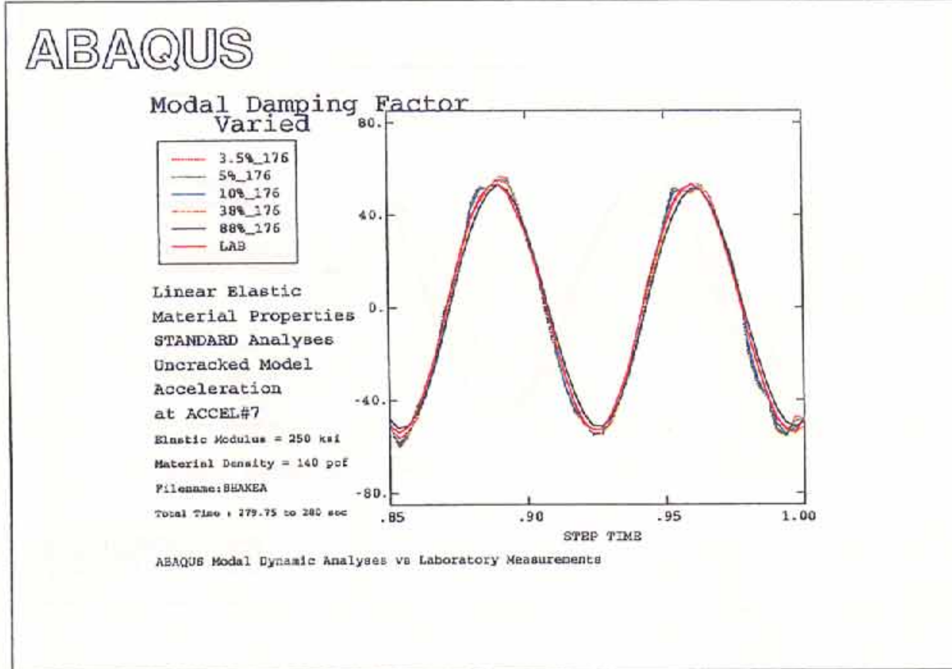
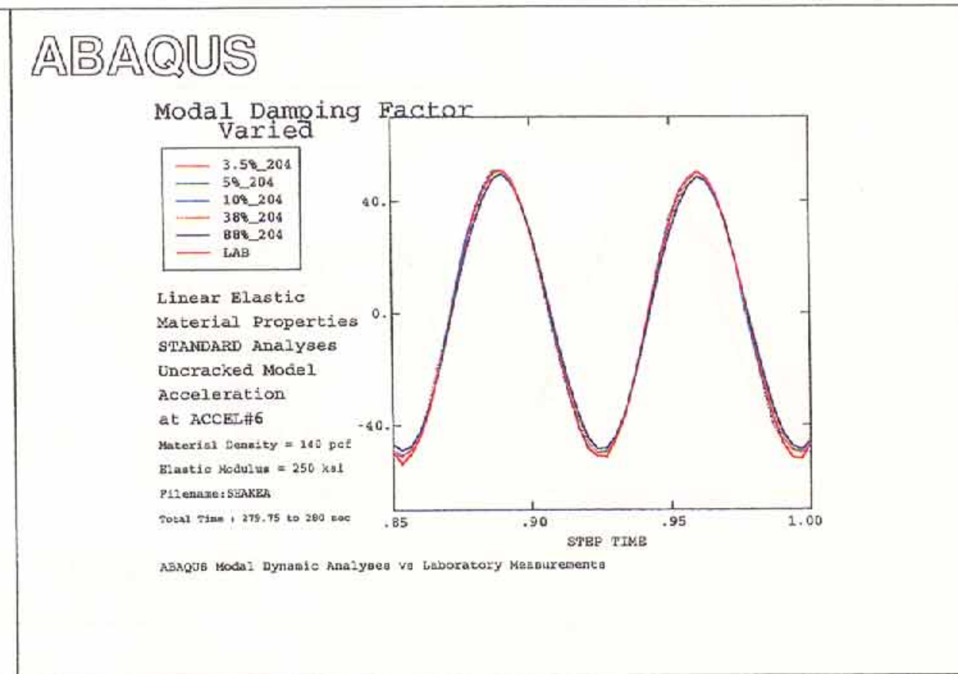
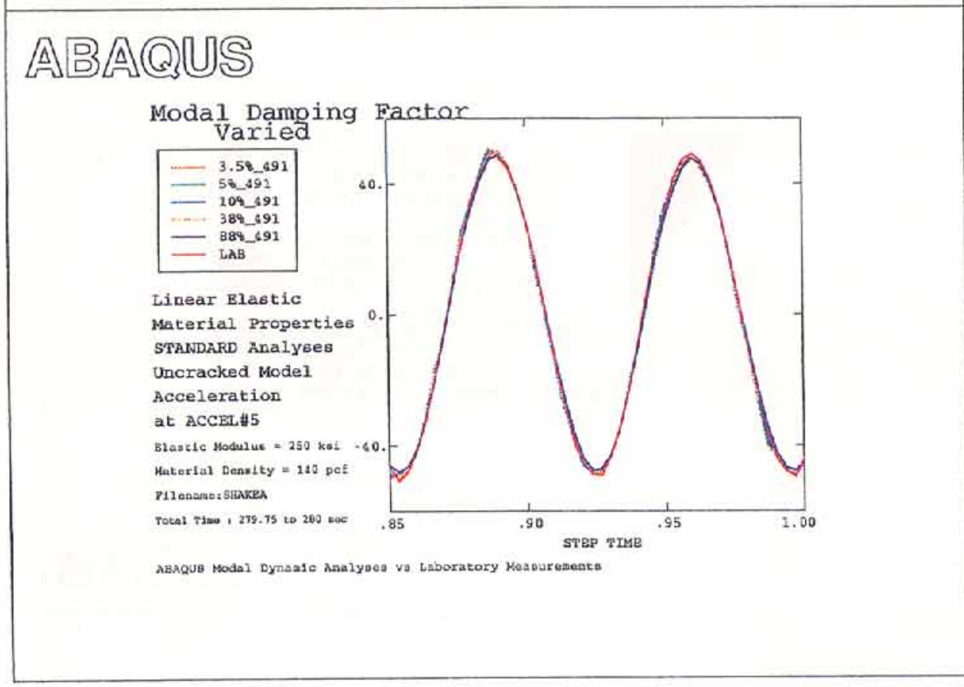

ABAQUS
Modal Damping Factor Varied
3.5%_176
5%_176
10%_176
38%_176
88%_176
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Elastic Modulus = 210 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements
ABAQUS
Modal Damping Factor Varied
3.5%_204
5%_204
10%_204
38%_204
88%_204
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements
ABAQUS
Modal Damping Factor Varied
3.5%_491
5%_491
10%_491
38%_491
88%_491
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Elastic Modulus = 210 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements
ABAQUS
Modal Damping Factor Varied
3.5%_519
5%_519
10%_519
38%_519
88%_519
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Elastic Modulus = 210 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

Figure h12


ABAQUS
Modal Damping Factor Varied
3.5%_176
5%_176
10%_176
38%_176
88%_176
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Elastic Modulus = 250 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements


ABAQUS
Modal Damping Factor Varied
3.5%_204
5%_204
10%_204
38%_204
88%_204
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Material Density = 140 pcf
Elastic Modulus = 250 ksi
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements


ABAQUS
Modal Damping Factor Varied
3.5%_491
5%_491
10%_491
38%_491
88%_491
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Elastic Modulus = 250 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

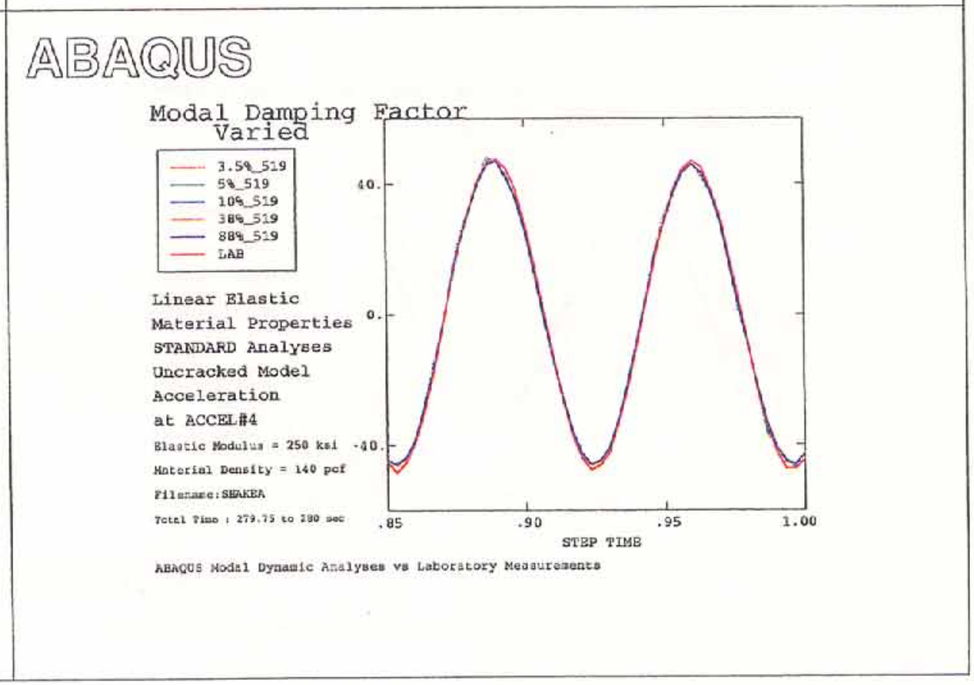

ABAQUS
Modal Damping Factor Varied
3.5%_519
5%_519
10%_519
38%_519
88%_519
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Elastic Modulus = 250 ksi
Material Density = 140 pcf
Filename:SHAKEA
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS Modal Dynamic Analyses vs Laboratory Measurements

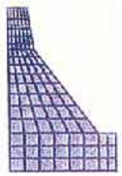
Figure h13

ABAQUS

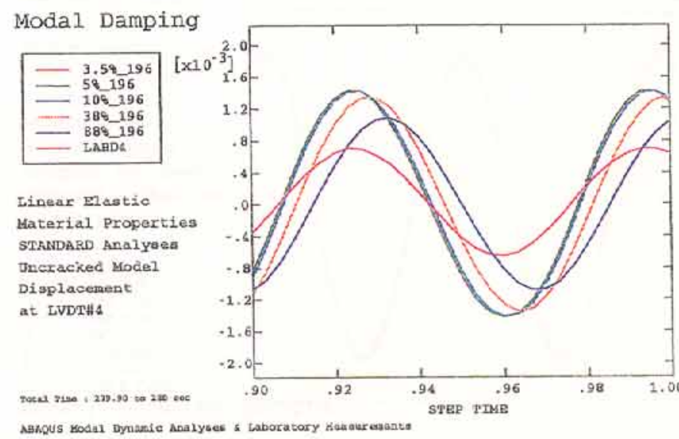
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Modal Damping

Comparison of Displacements
ABAQUS STANDARD
Modal Dynamic Analysis

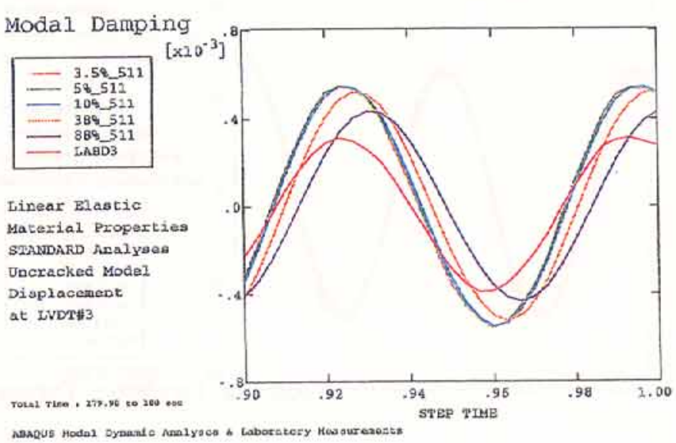
Input Record SHAKEA
Elastic Modulus = 190 ksi
Density = 133.0 pcf
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

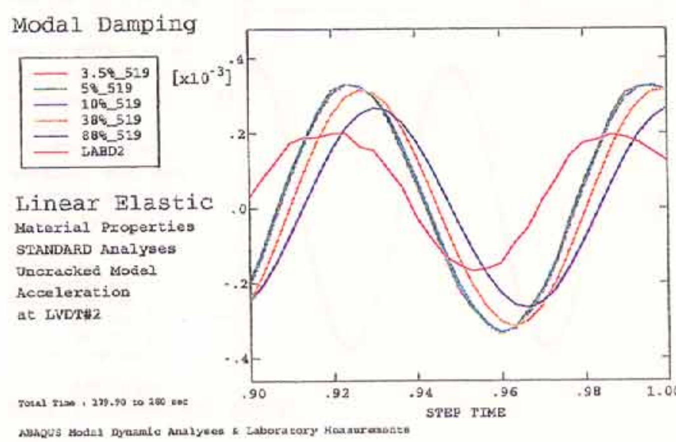


Figure h14

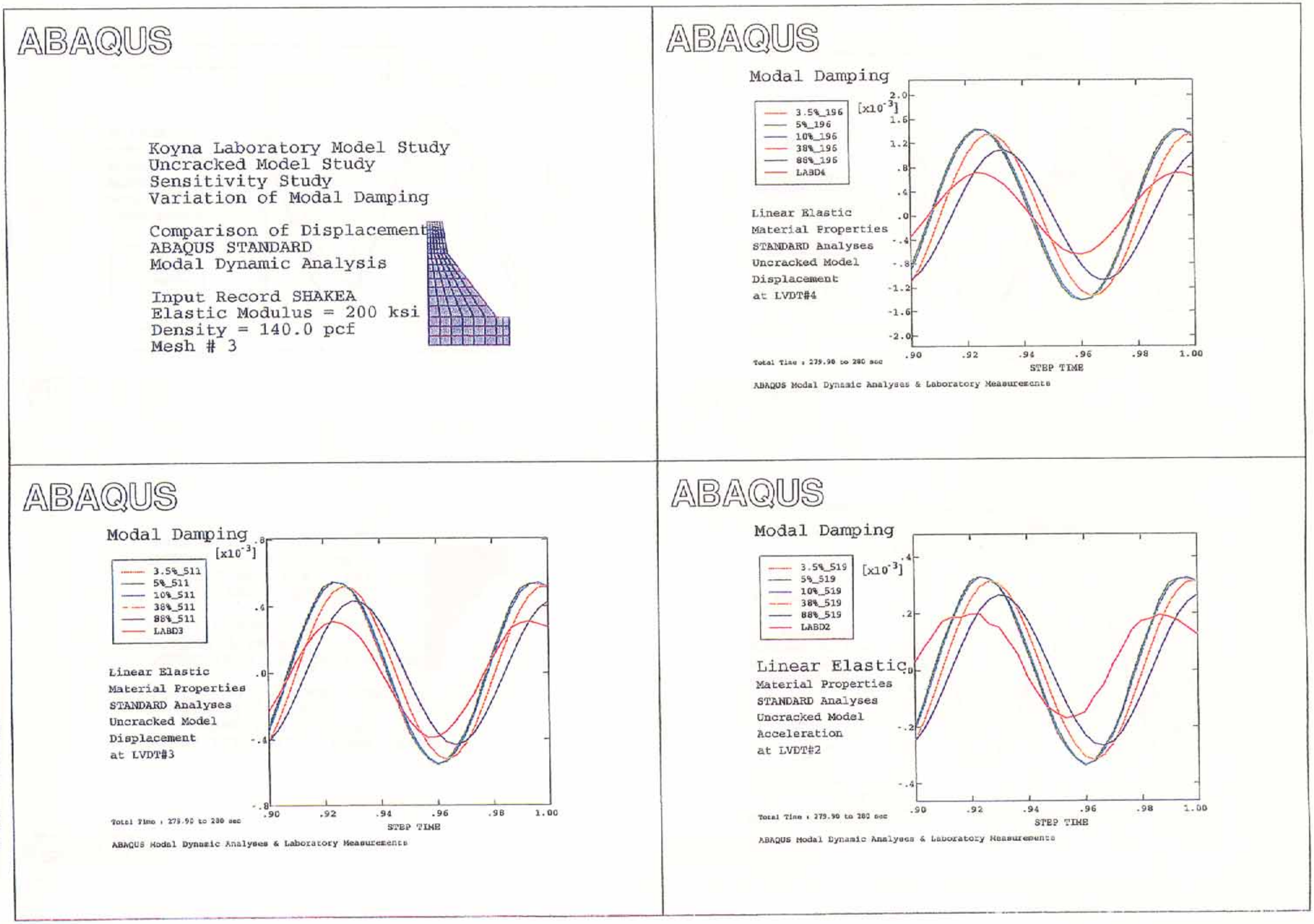

ABAQUS
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Modal Damping
Comparison of Displacement
ABAQUS STANDARD
Modal Dynamic Analysis
Input Record SHAKEA
Elastic Modulus = 200 ksi
Density = 140.0 pcf
Mesh # 3
ABAQUS
Modal Damping
3.5%_196
5%_196
10%_196
38%_196
88%_196
LABD4
[x10^-3]
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Displacement
at LVDT#4
.90
.92
.94
.96
.98
1.00
Total Time : 279.90 to 280 sec
STEP TIME
ABAQUS Modal Dynamic Analyses & Laboratory Measurements
ABAQUS
Modal Damping
[x10^-3]
3.5%_511
5%_511
10%_511
38%_511
88%_511
LABD3
.8
.4
.0
-.4
-.8
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Displacement
at LVDT#3
.90
.92
.94
.96
.98
1.00
Total Time : 279.90 to 280 sec
STEP TIME
ABAQUS Modal Dynamic Analyses & Laboratory Measurements
ABAQUS
Modal Damping
3.5%_519
5%_519
10%_519
38%_519
88%_519
LABD2
[x10^-3]
.4
.2
0
-.2
-.4
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at LVDT#2
.90
.92
.94
.96
.98
1.00
Total Time : 279.90 to 280 sec
STEP TIME
ABAQUS Modal Dynamic Analyses & Laboratory Measurements

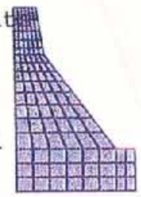
Figure h15

ABAQUS

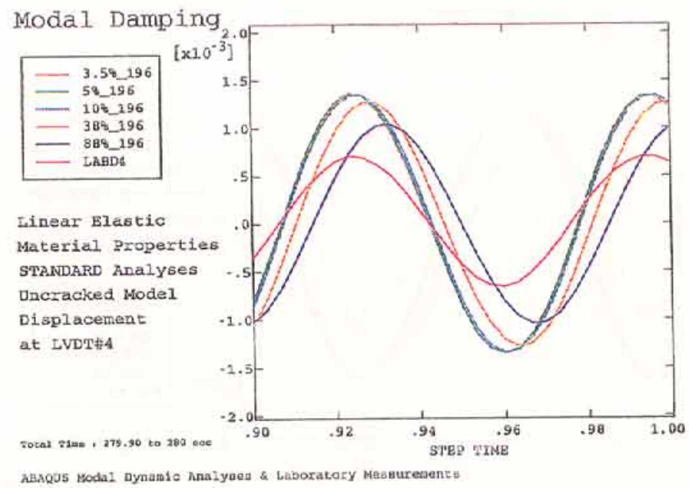
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Modal Damping

Comparison of Displacement
ABAQUS STANDARD
Modal Dynamic Analysis

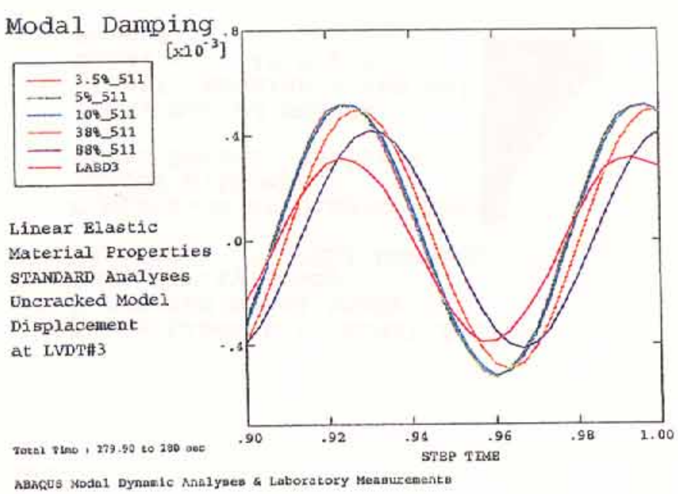
Input Record SHAKEA
Elastic Modulus = 210 ksi
Density = 140.0 pcf
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

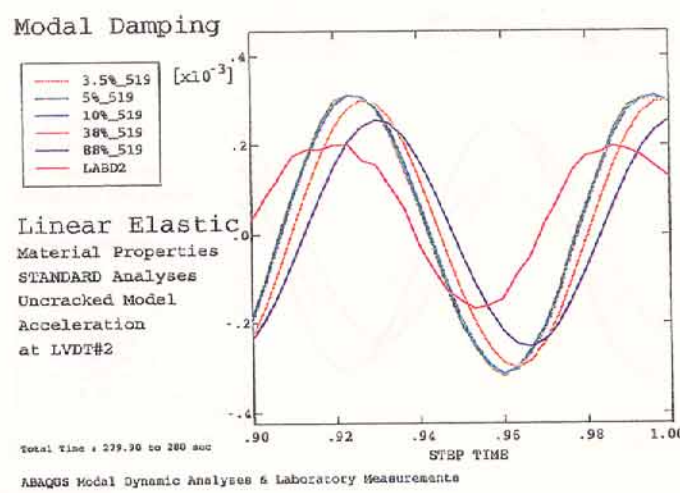


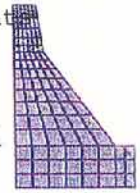
Figure h16

ABAQUS

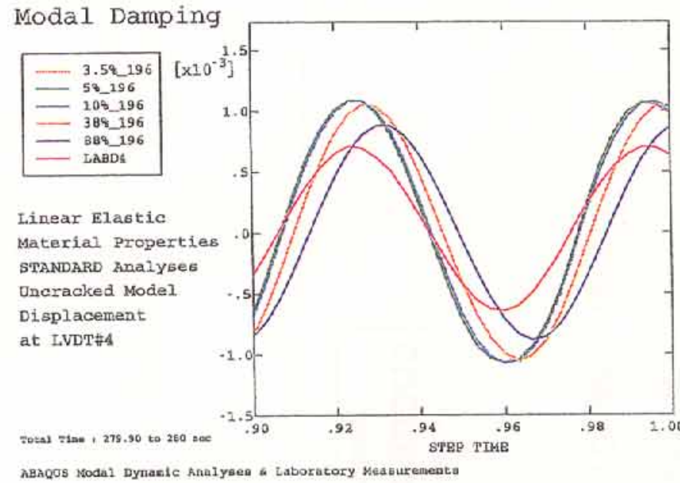
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Modal Damping

Comparison of Displacements
ABAQUS STANDARD
Modal Dynamic Analysis

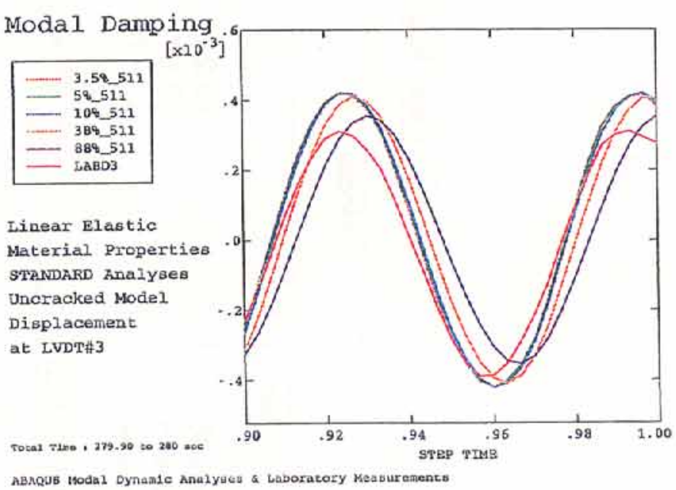
Input Record SHAKEA
Elastic Modulus = 250 ksi
Density = 140.0 pcf
Mesh # 3



ABAQUS



ABAQUS



ABAQUS

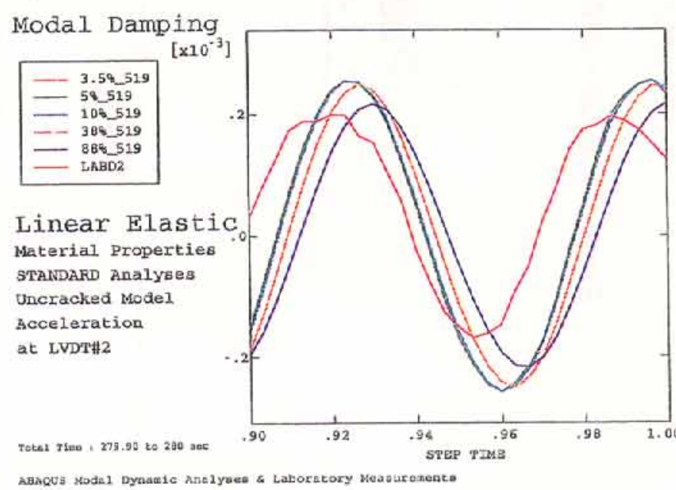
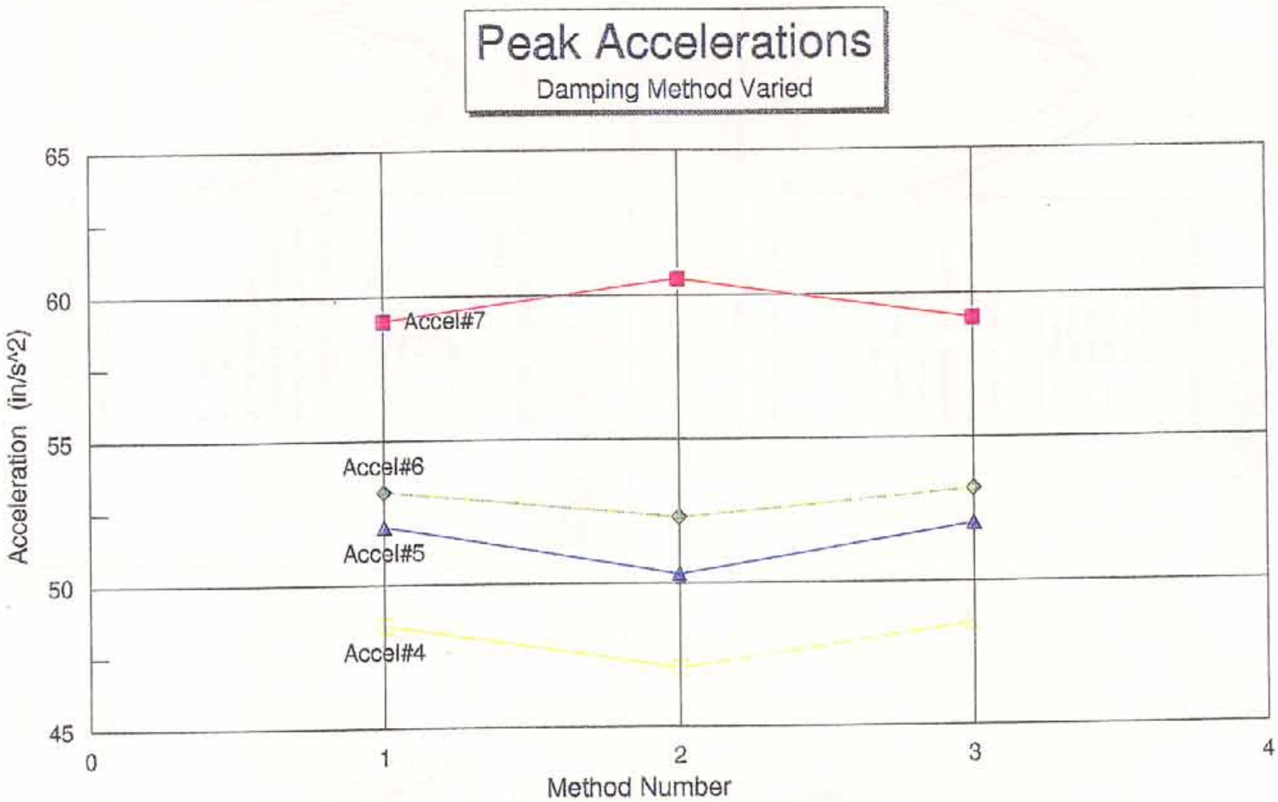


Figure h17

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Damping Method
Mesh#3
Modal Damping; Rayleigh Damping; Composite Damping
10 Percent of Critical Damping

Elastic Modulus = 210 ksi; Material Density = 138.2 pcf



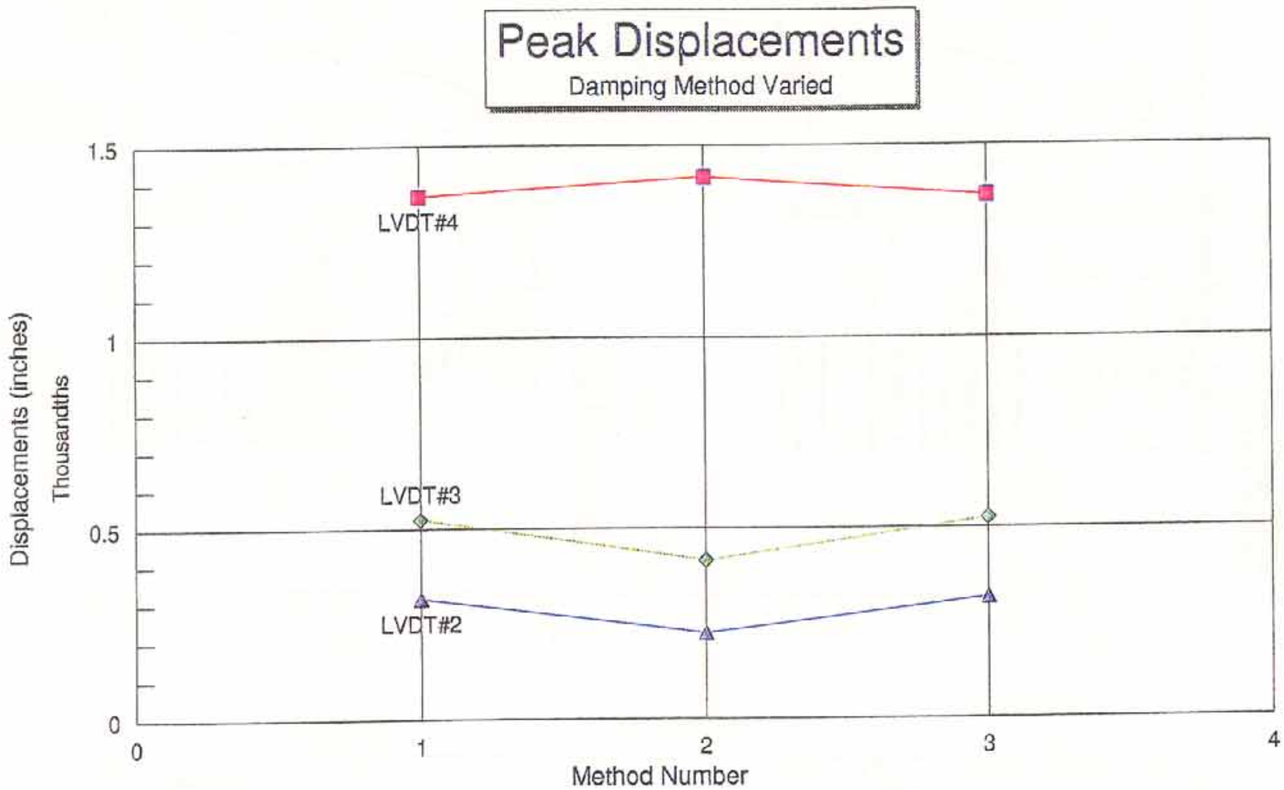
Peak Accelerations (inch / sec ^ 2)

	Modal	Rayleigh	Composite	
Method Number	1	2	3	LAB
Accel#7	59.15	60.57	59.15	53.26
Accel#6	53.21	52.29	53.21	51.72
Accel#5	52.02	50.31	52.02	49.26
Accel#4	48.57	47.06	48.57	47.72
CPU TIME (SEC)	264	264	263	

Figure h18

Uncracked Koyna Laboratory Study
Sensitivity to Variation in Damping Method
Mesh#3
Modal Damping; Rayleigh Damping; Composite Damping
10 Percent of Critical Damping

Elastic Modulus = 210 ksi; Material Density = 138.2 pcf



Peak Displacements (inches)				
	Modal	Rayleigh	Composite	
Method Number	1	2	3	LAB
LVDT#4	1.4E-03	1.4E-03	1.4E-03	7.8E-04
LVDT#3	5.2E-04	4.1E-04	5.2E-04	3.0E-04
LVDT#2	3.2E-04	2.2E-04	3.2E-04	1.8E-04
CPU TIME (SEC)	264	264	263	

Figure h19

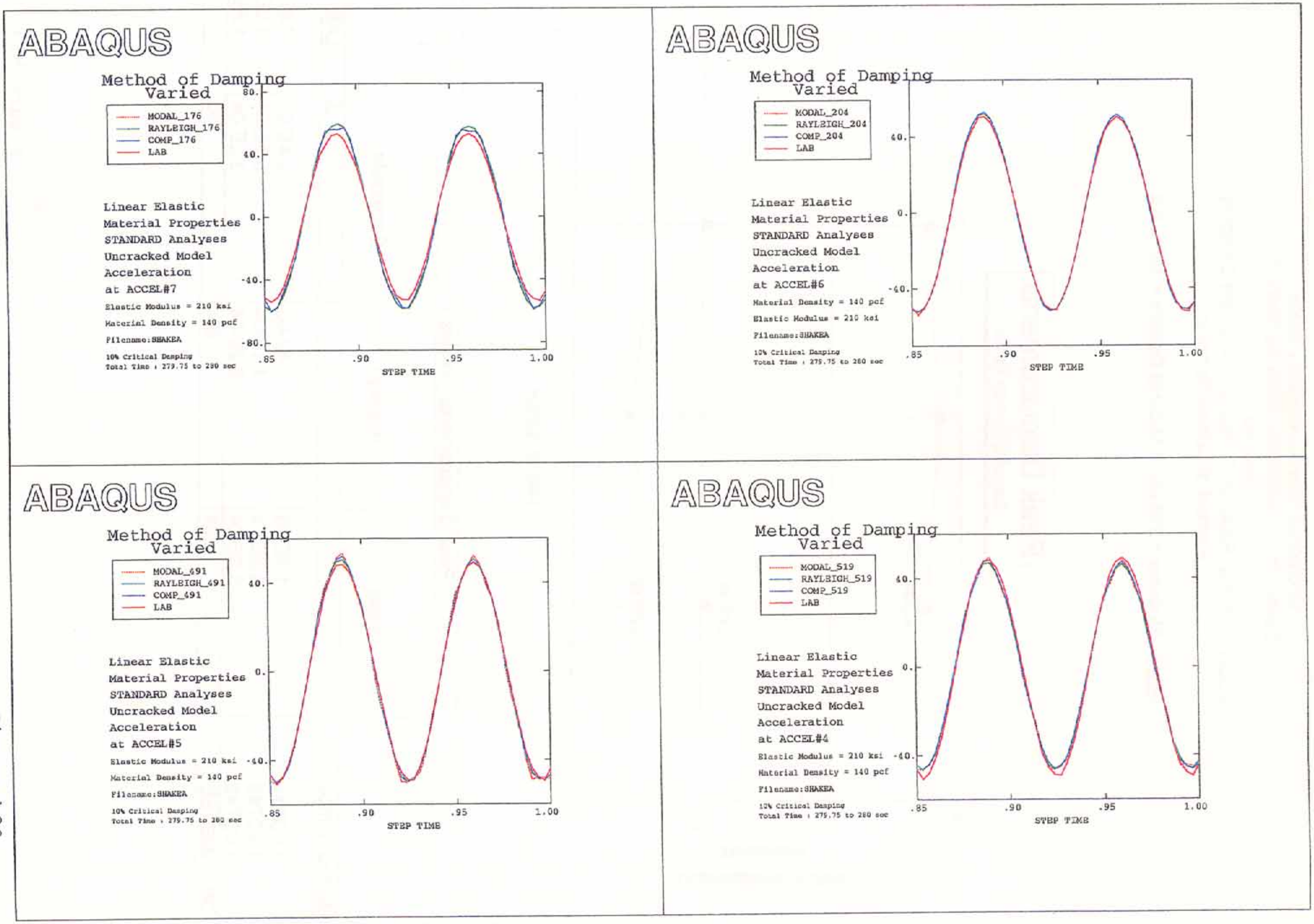

ABAQUS
Method of Damping Varied
MODAL_176
RAYLEIGH_176
COMP_176
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#7
Elastic Modulus = 210 ksi
Material Density = 140 pcf
Filename:SHAKEA
10% Critical Damping
Total Time : 279.75 to 280 sec
80.
40.
0.
-40.
-80.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Method of Damping Varied
MODAL_204
RAYLEIGH_204
COMP_204
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#6
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename:SHAKEA
10% Critical Damping
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Method of Damping Varied
MODAL_491
RAYLEIGH_491
COMP_491
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#5
Elastic Modulus = 210 ksi
Material Density = 140 pcf
Filename:SHAKEA
10% Critical Damping
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Method of Damping Varied
MODAL_519
RAYLEIGH_519
COMP_519
LAB
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at ACCEL#4
Elastic Modulus = 210 ksi
Material Density = 140 pcf
Filename:SHAKEA
10% Critical Damping
Total Time : 279.75 to 280 sec
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME

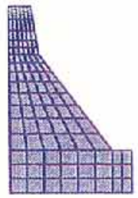
Figure h20

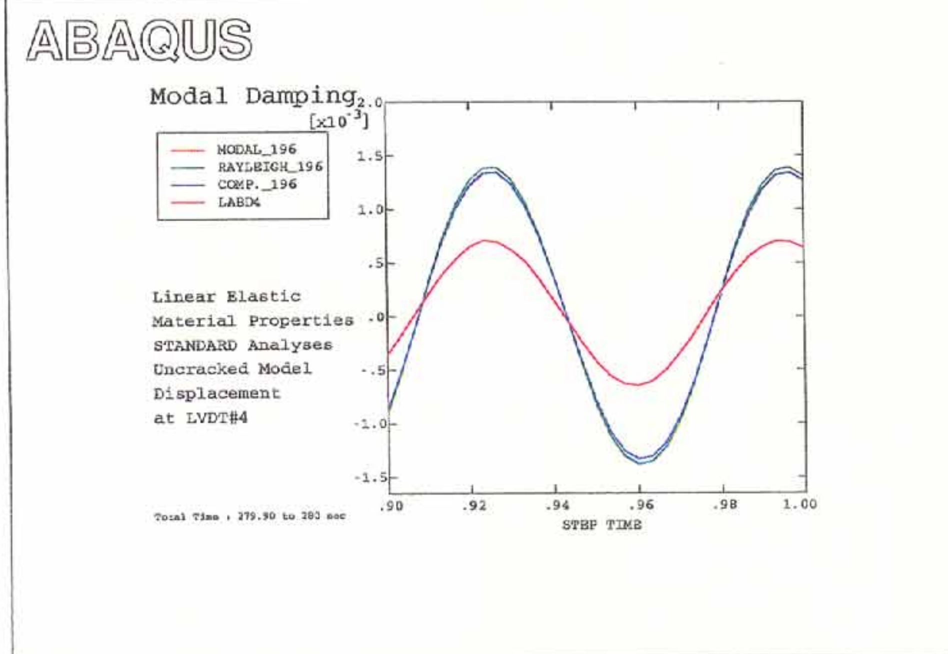
ABAQUS

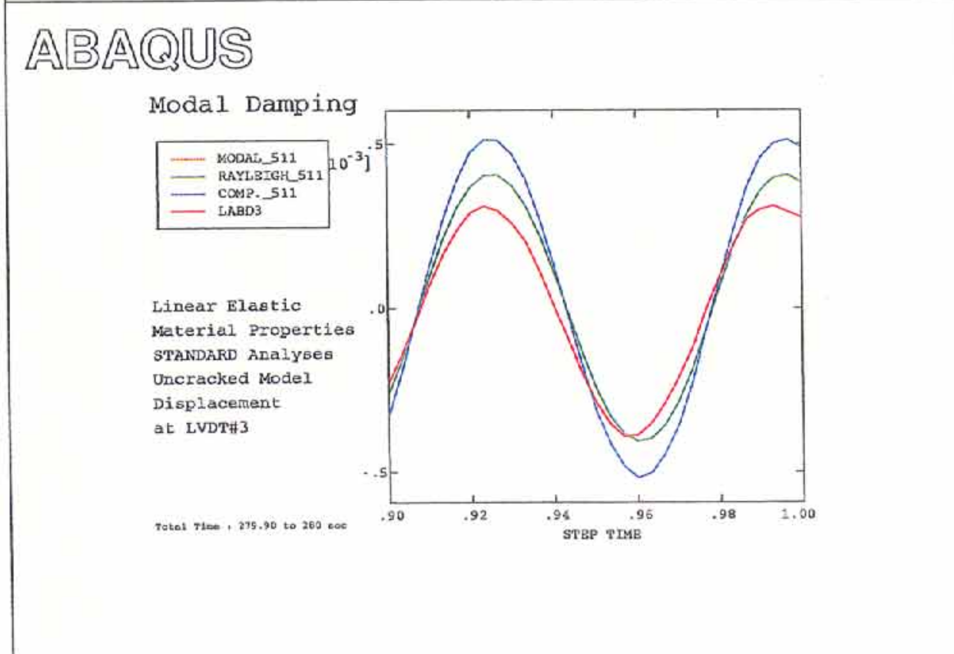
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Damping Method

Comparison of Displacements
ABAQUS STANDARD
Modal Dynamic Analysis

Input Record SHAKEA
Elastic Modulus = 210 ksi
Density = 140.0 pcf
Mesh # 3
10 Percent Critical Damping







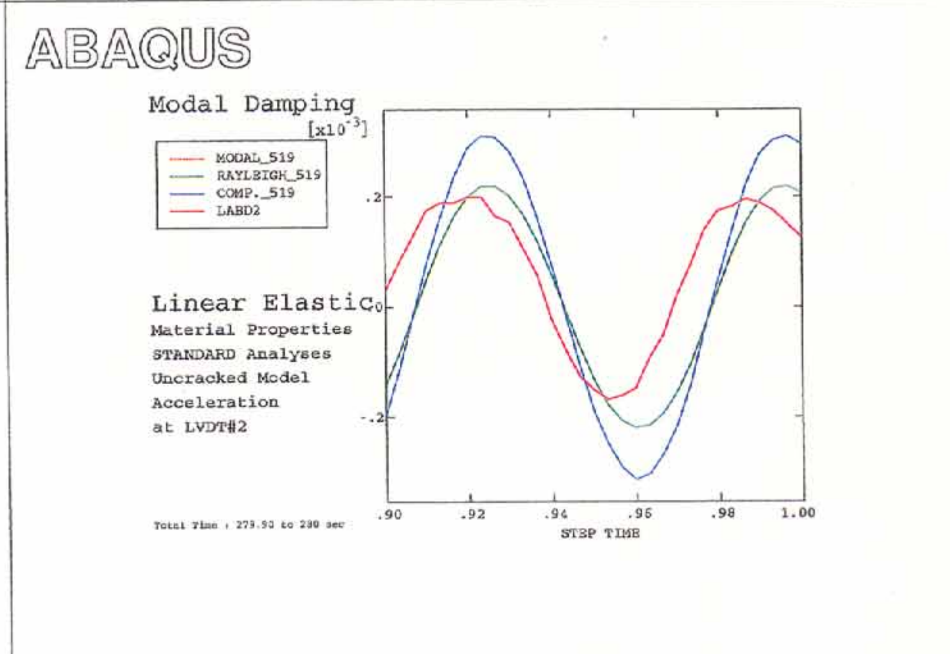
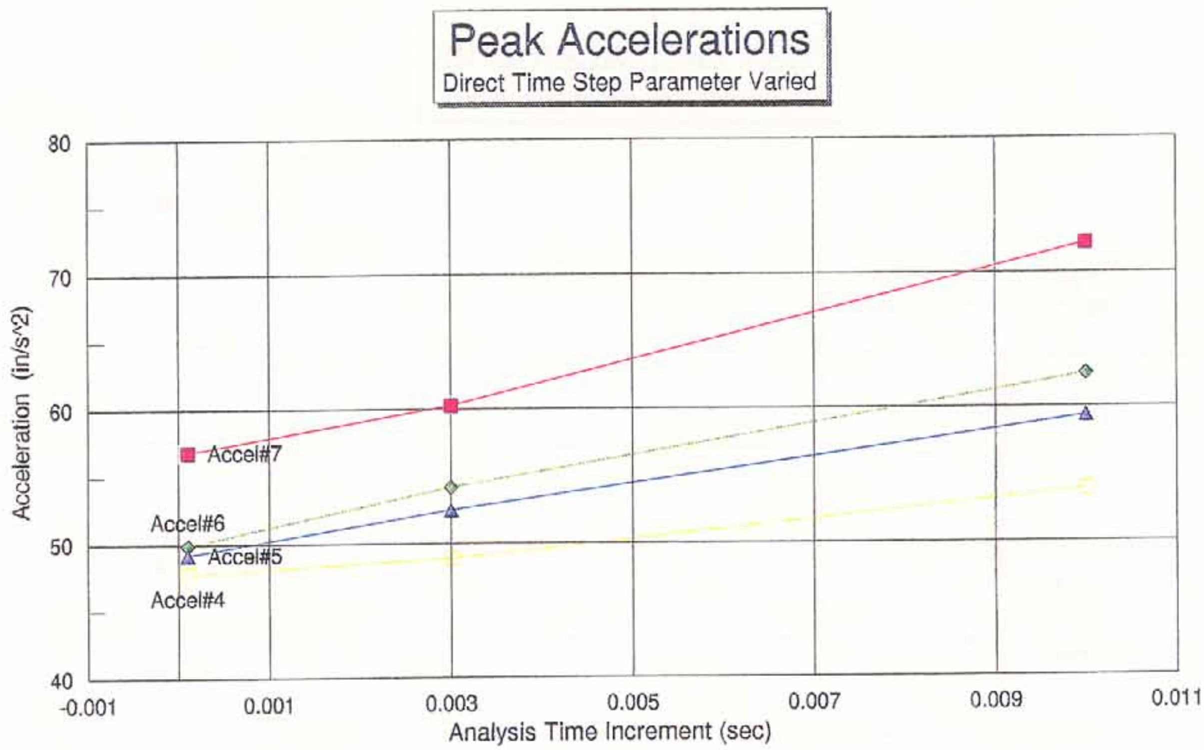


Figure h21

Uncracked Koyna Laboratory Study

Direct Integration Dynamic Analysis
Sensitivity to Variation in Direct Time Step Parameter
Mesh#3

Elastic Modulus = 210 ksi; Material Density = 140 pcf



Peak Accelerations (inch / sec ^ 2)

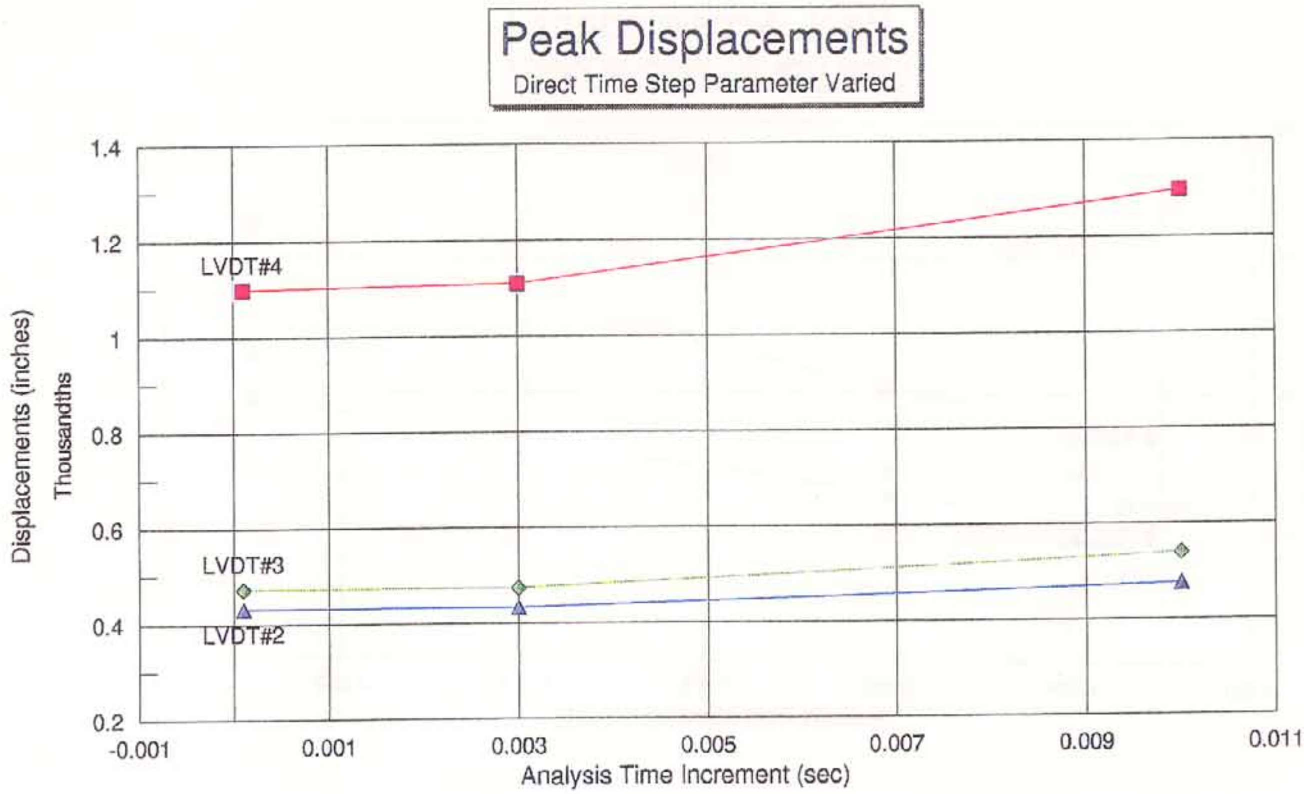
Direct Time Step	0.0001	0.003	0.01	LAB
Accel#7	56.81	60.26	72.18	53.26
Accel#6	49.87	54.17	62.47	51.72
Accel#5	49.19	52.47	59.36	49.26
Accel#4	47.75	48.86	53.94	47.72
CPU Time (sec)	39564	1441	557	

Figure i1

Uncracked Koyna Laboratory Study

Direct Integration Dynamic Analysis
Sensitivity to Variation in Direct Time Increment Parameter
Mesh#3

Elastic Modulus = 210 ksi; Material Density = 140 pcf



Peak Displacements (inches)				
Haftol Parameter	0.0001	0.003	0.01	LAB
LVDT#4 LVDT#3 LVDT#2	1.1E-03 4.7E-04 4.3E-04	1.1E-03 4.7E-04 4.3E-04	1.3E-03 5.4E-04 4.7E-04	7.8E-04 3.0E-04 1.8E-04
CPU Time (sec)	39564	1441	557	

Figure i2

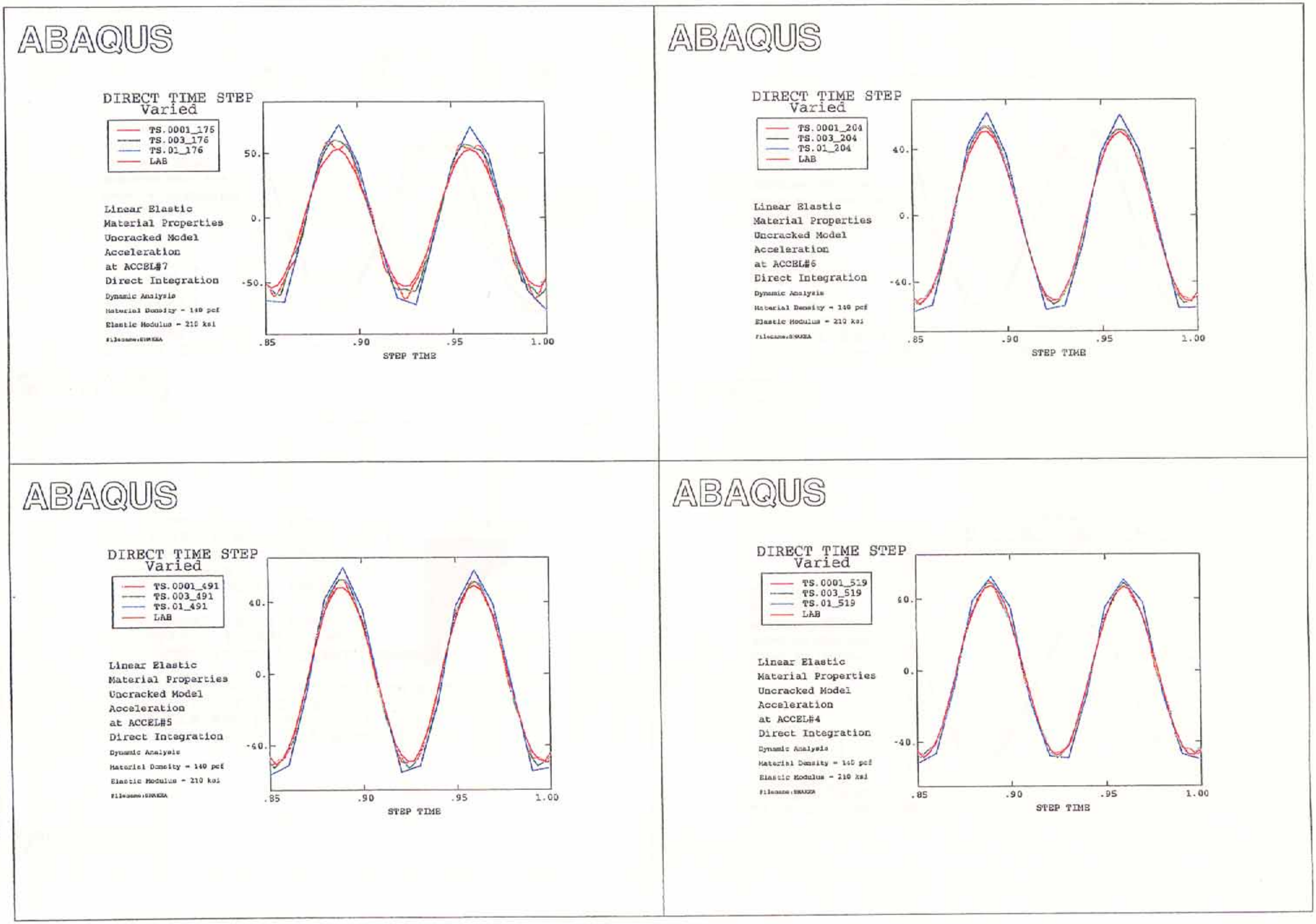

ABAQUS
DIRECT TIME STEP Varied
TS.0001_175
TS.003_176
TS.01_176
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#7
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
50.
0.
-50.
.85
.90
.95
1.00
STEP TIME
ABAQUS
DIRECT TIME STEP Varied
TS.0001_204
TS.003_204
TS.01_204
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#6
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS
DIRECT TIME STEP Varied
TS.0001_491
TS.003_491
TS.01_491
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#5
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS
DIRECT TIME STEP Varied
TS.0001_519
TS.003_519
TS.01_519
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#4
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME

Figure 13

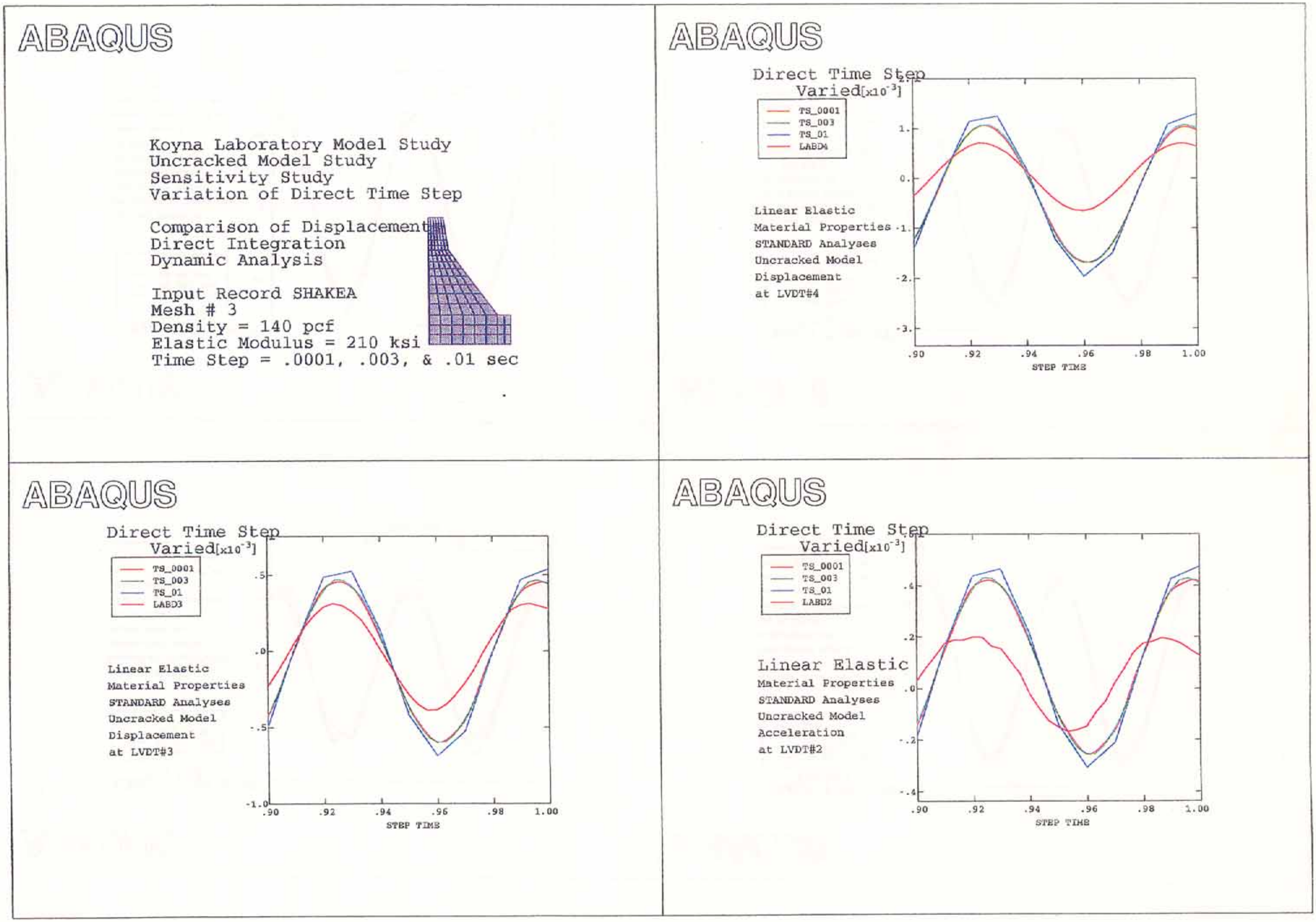
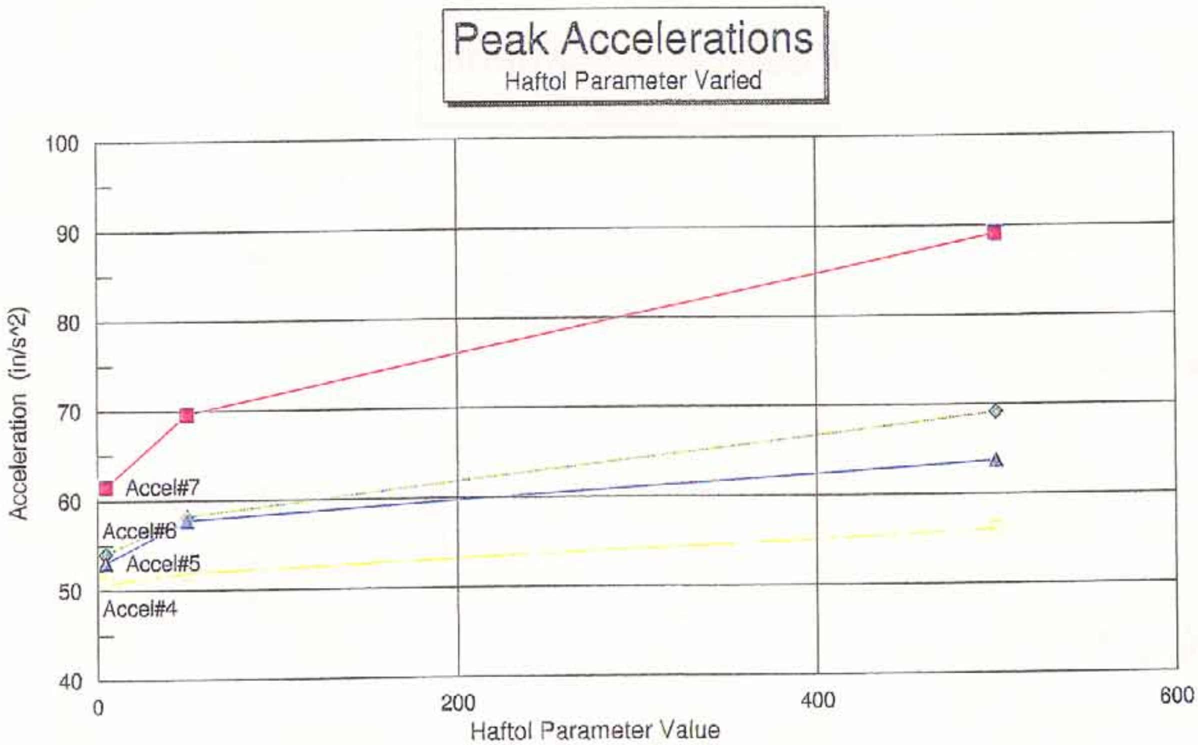

ABAQUS
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Direct Time Step
Comparison of Displacement
Direct Integration
Dynamic Analysis
Input Record SHAKEA
Mesh # 3
Density = 140 pcf
Elastic Modulus = 210 ksi
Time Step = .0001, .003, & .01 sec
ABAQUS
Direct Time Step
Varied[x10^-3]
TS_0001
TS_003
TS_01
LABD4
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Displacement
at LVDT#4
2.
1.
0.
-1.
-2.
-3.
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS
Direct Time Step
Varied[x10^-3]
TS_0001
TS_003
TS_01
LABD3
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Displacement
at LVDT#3
.5
.0
-.5
-1.0
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS
Direct Time Step
Varied[x10^-3]
TS_0001
TS_003
TS_01
LABD2
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at LVDT#2
.6
.4
.2
.0
-.2
-.4
.90
.92
.94
.96
.98
1.00
STEP TIME

Figure 14

Uncracked Koyna Laboratory Study

Direct Integration Dynamic Analysis
Sensitivity to Variation in Haftol Parameter
Mesh#3

Elastic Modulus = 210 ksi; Material Density = 140 pcf



Peak Accelerations (inch / sec ^ 2)

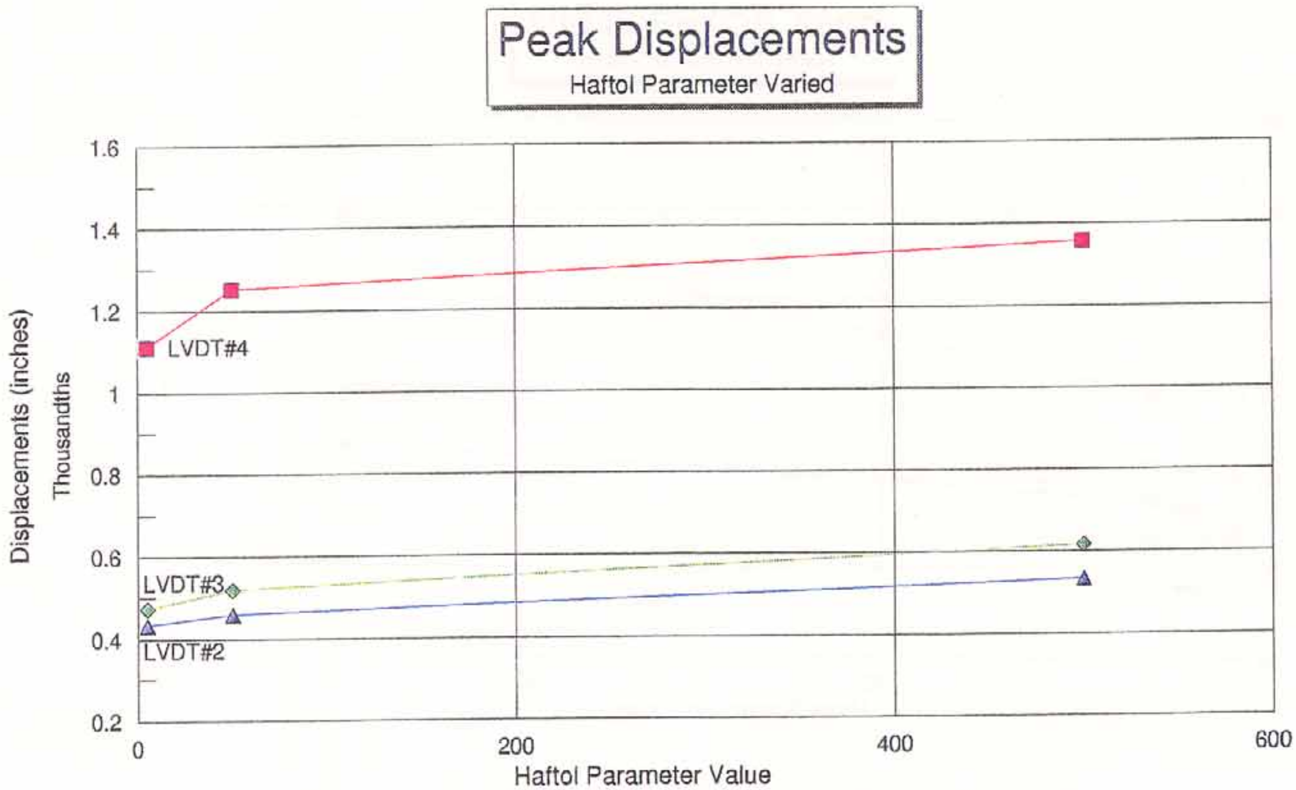
Haftol Parameter	5	50	500	LAB
Accel#7	61.51	69.62	89.07	53.26
Accel#6	54.09	58.23	69.14	51.72
Accel#5	53.04	57.73	63.71	49.26
Accel#4	50.75	51.88	56.01	47.72
CPU Time (sec)	3179	1230	785	

Figure i5

Uncracked Koyna Laboratory Study

Direct Integration Dynamic Analysis
Sensitivity to Variation in Haftol Parameter
Mesh#3

Elastic Modulus = 210 ksi; Material Density = 140 pcf



Peak Displacements (inches)				
Haftol Parameter	5	50	500	LAB
LVDT#4 LVDT#3 LVDT#2	1.1E-03 4.7E-04 4.3E-04	1.3E-03 5.2E-04 4.6E-04	1.4E-03 6.2E-04 5.3E-04	7.8E-04 3.0E-04 1.8E-04
CPU Time (sec)	3179	1230	785	

Figure i6

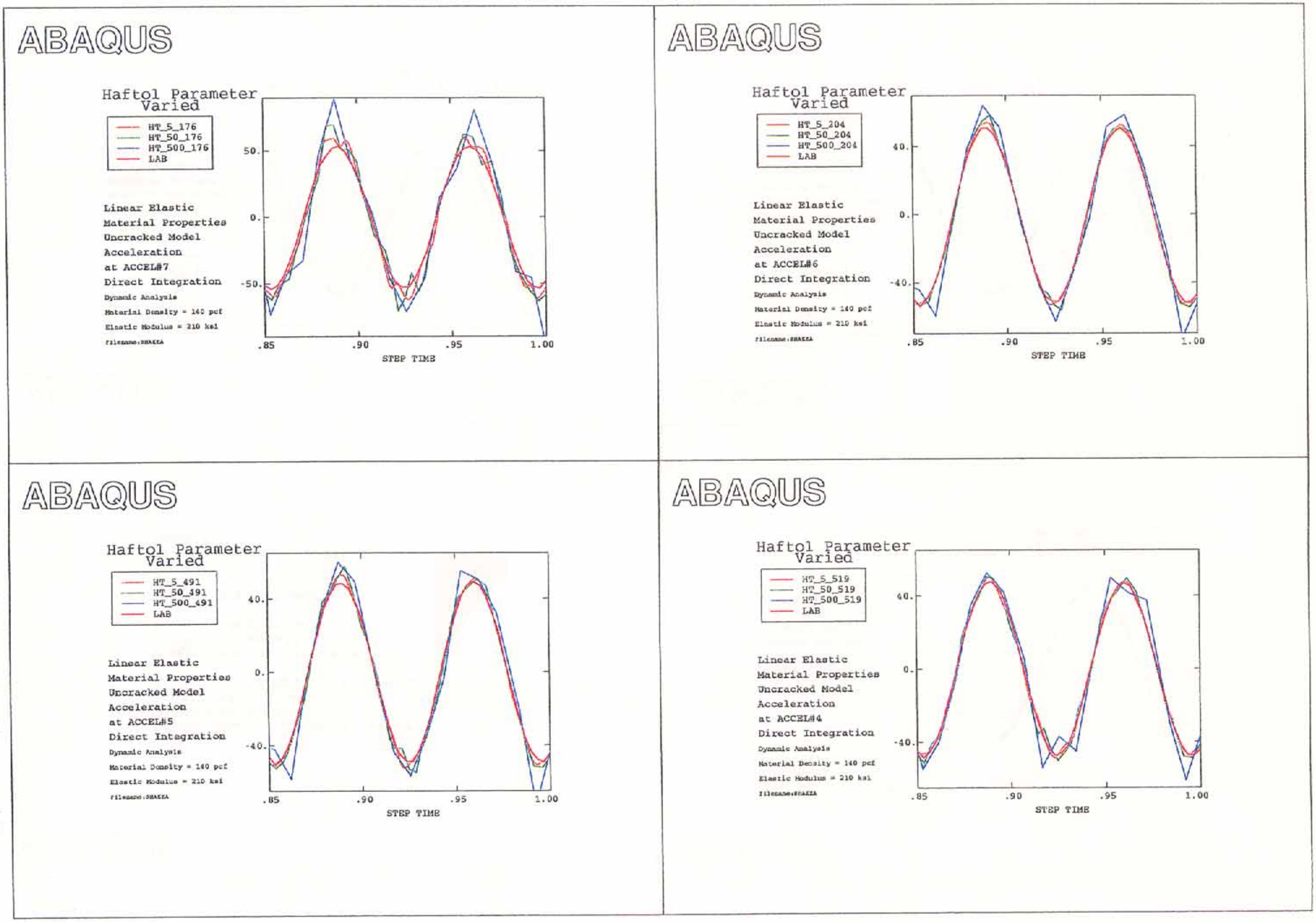

ABAQUS
Haftol Parameter Varied
HT_5_176
HT_50_176
HT_500_176
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#7
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
50.
0.
-50.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Haftol Parameter Varied
HT_5_204
HT_50_204
HT_500_204
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#6
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Haftol Parameter Varied
HT_5_491
HT_50_491
HT_500_491
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#5
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Haftol Parameter Varied
HT_5_519
HT_50_519
HT_500_519
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#4
Direct Integration
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME

Figure 17

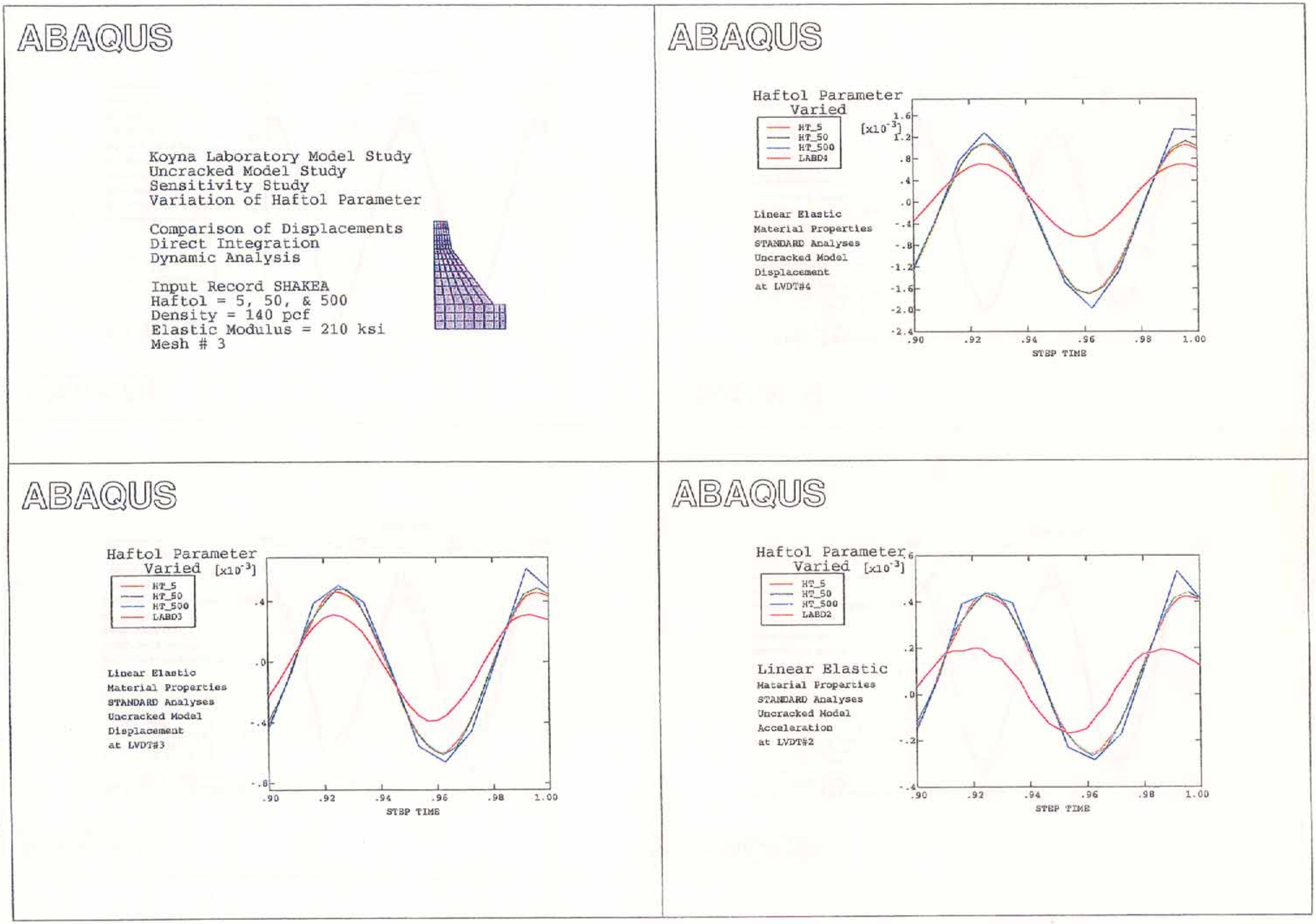
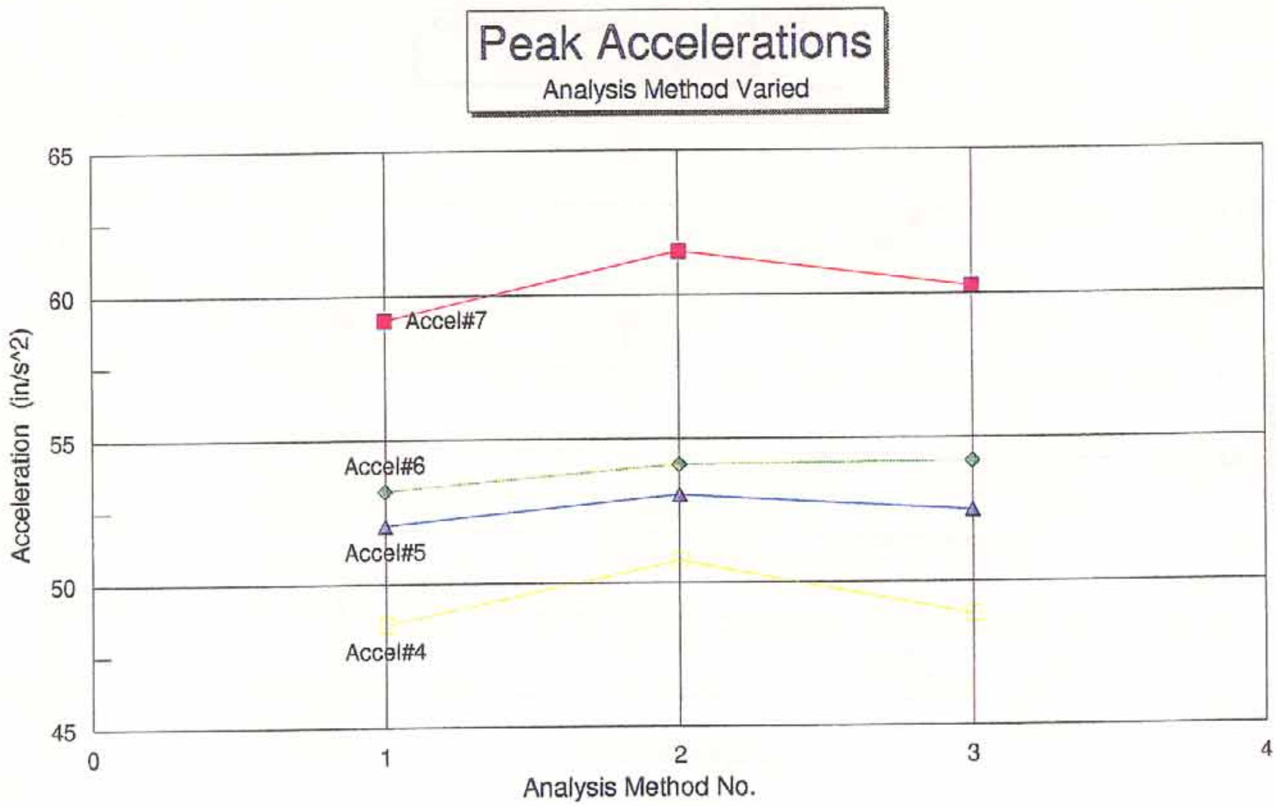

ABAQUS
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Haftol Parameter
Comparison of Displacements
Direct Integration
Dynamic Analysis
Input Record SHAKEA
Haftol = 5, 50, & 500
Density = 140 pcf
Elastic Modulus = 210 ksi
Mesh # 3
ABAQUS
Haftol Parameter Varied
HT_5
HT_50
HT_500
LABD4
[x10^-3]
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Displacement
at LVDT#4
STEP TIME
ABAQUS
Haftol Parameter Varied
[x10^-3]
HT_5
HT_50
HT_500
LABD3
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Displacement
at LVDT#3
STEP TIME
ABAQUS
Haftol Parameter Varied
[x10^-3]
HT_5
HT_50
HT_500
LABD2
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at LVDT#2
STEP TIME

Figure 18

Uncracked Koyna Laboratory Study
Sensitivity to Variation Analysis Method
Mesh#3
Modal Analysis Methods
Direct Integration using Haftol Parameter = 5
Direct Integration using Direct time Step = .003 sec
Modal Analysis
10 Percent of Critical Damping
Elastic Modulus = 210 ksi;   Material Density = 139 pcf

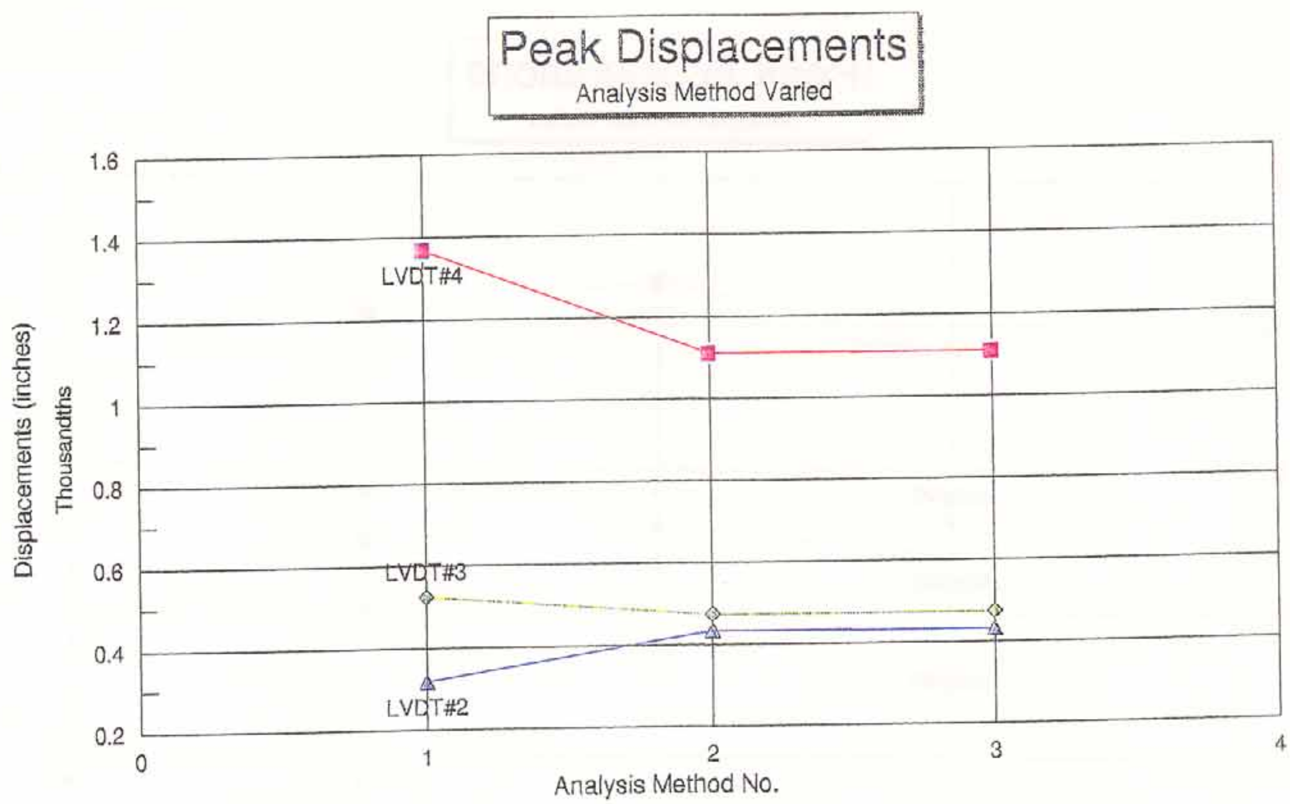


Peak Accelerations (inch / sec ^ 2)

	Modal	Direct Haftol=5	Direct Time Step=.003	
Method Number	1	2	3	LAB
Accel#7	59.15	61.51	60.26	53.26
Accel#6	53.21	54.09	54.17	51.72
Accel#5	52.02	53.04	52.47	49.26
Accel#4	48.57	50.75	48.86	47.72
CPU TIME (SEC)	264	3179	1441	

Figure j1

Uncracked Koyna Laboratory Study
Sensitivity to Variation Analysis Method
Mesh#3
Modal Analysis Methods
Direct Integration using Haftol Parameter = 5
Direct Integration using Direct time Step = .003 sec
Modal Analysis
10 Percent of Critical Damping
Elastic Modulus = 210 ksi;   Material Density = 139 pcf



Peak Displacements (inches)

	Modal	Direct Haftol=5	Direct Time Step=.003	
Method Number	1	2	3	LAB
LVDT#4 LVDT#3 LVDT#2	1.4E-03 5.2E-04 3.2E-04	1.1E-03 4.7E-04 4.3E-04	1.1E-03 4.7E-04 4.3E-04	7.8E-04 3.0E-04 1.8E-04
CPU TIME (SEC)	264	3179	1441	

Figure j2

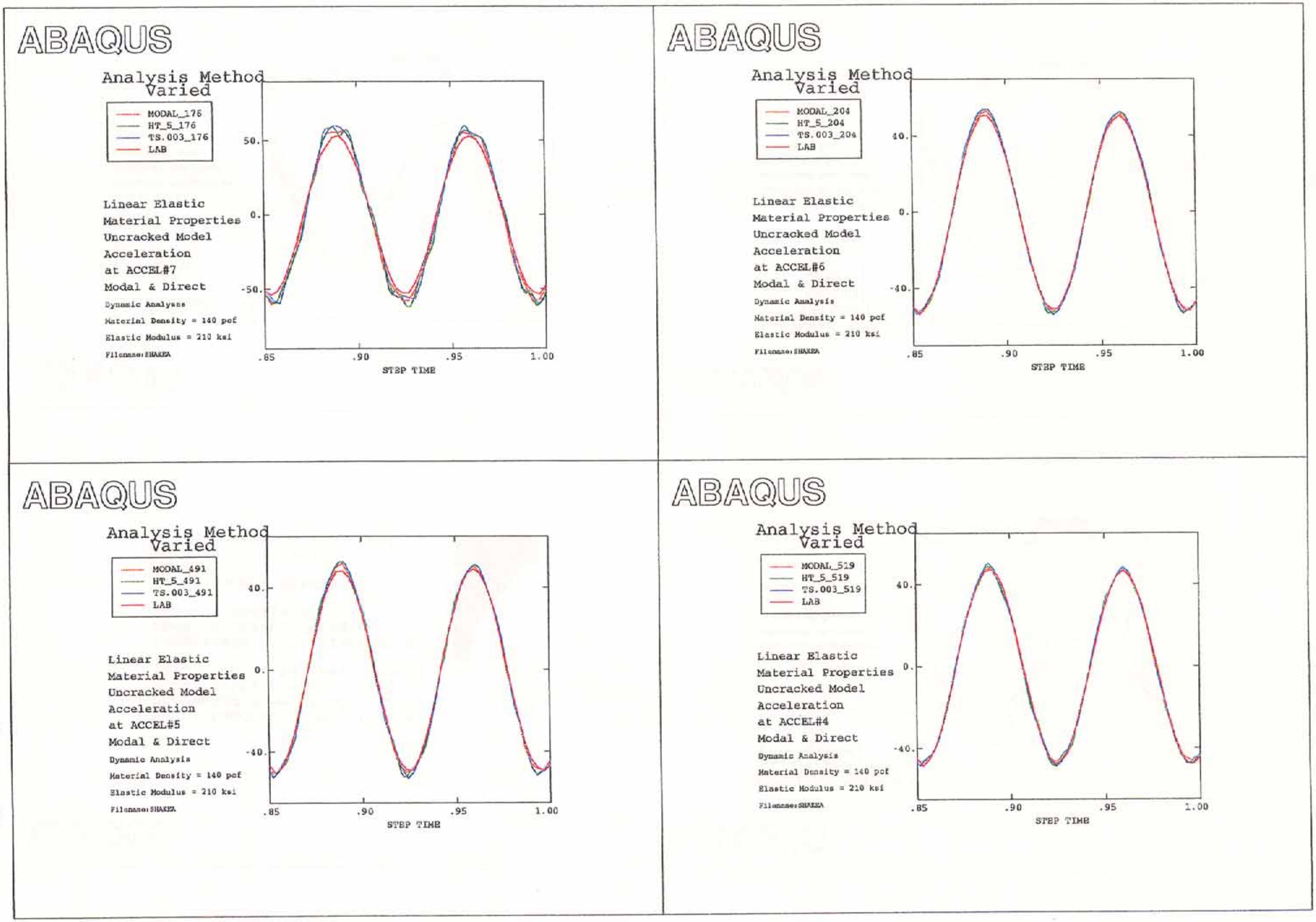

ABAQUS
Analysis Method Varied
MODAL_176
HT_5_176
TS.003_176
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#7
Modal & Direct
Dynamic Analyses
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename: SHAKEA
50.
0.
-50.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Analysis Method Varied
MODAL_204
HT_5_204
TS.003_204
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#6
Modal & Direct
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename: SHAKEA
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Analysis Method Varied
MODAL_491
HT_5_491
TS.003_491
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#5
Modal & Direct
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename: SHAKEA
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME
ABAQUS
Analysis Method Varied
MODAL_519
HT_5_519
TS.003_519
LAB
Linear Elastic
Material Properties
Uncracked Model
Acceleration
at ACCEL#4
Modal & Direct
Dynamic Analysis
Material Density = 140 pcf
Elastic Modulus = 210 ksi
Filename: SHAKEA
40.
0.
-40.
.85
.90
.95
1.00
STEP TIME

Figure 13

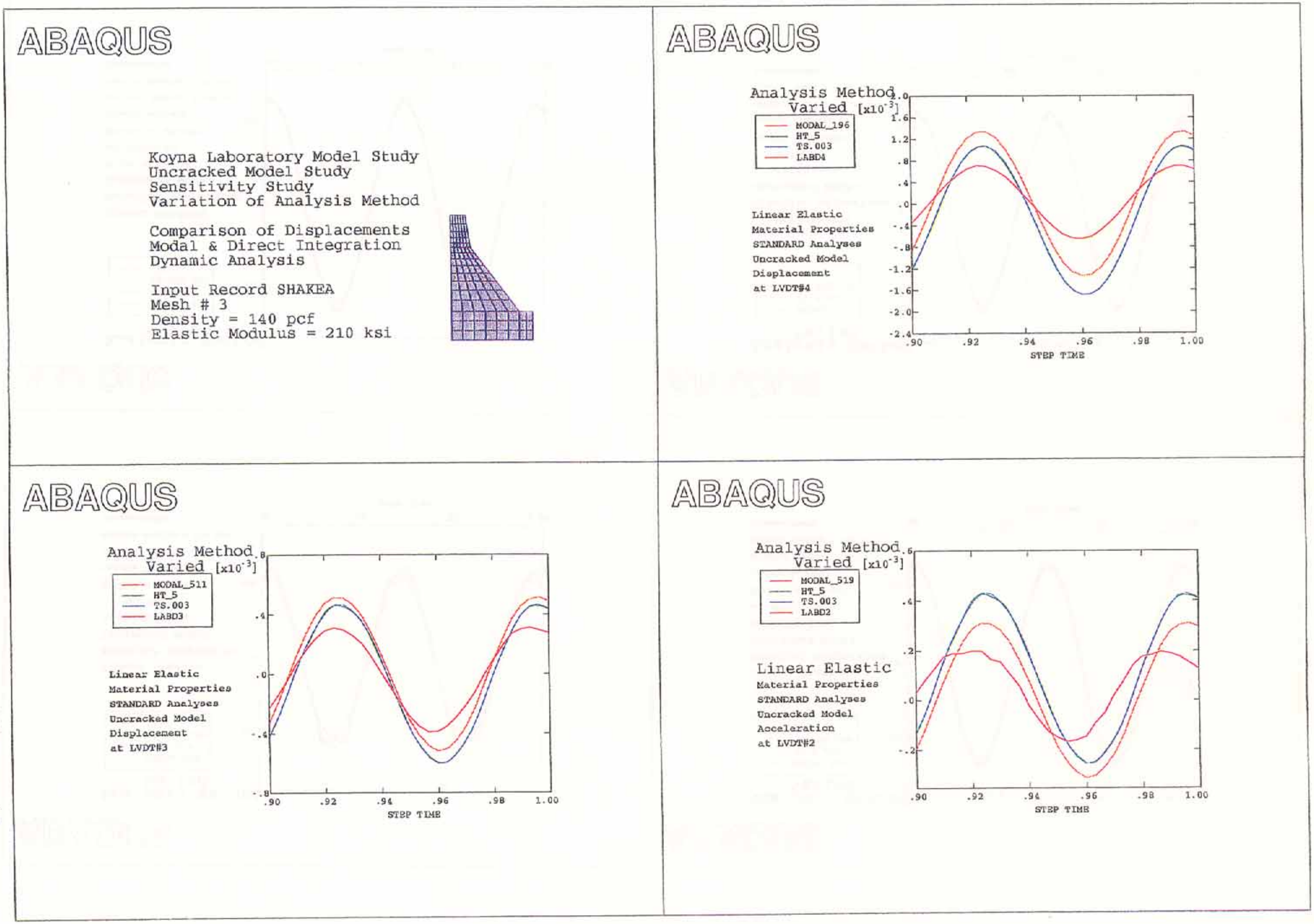

ABAQUS
Koyna Laboratory Model Study
Uncracked Model Study
Sensitivity Study
Variation of Analysis Method
Comparison of Displacements
Modal & Direct Integration
Dynamic Analysis
Input Record SHAKEA
Mesh # 3
Density = 140 pcf
Elastic Modulus = 210 ksi
ABAQUS
Analysis Method Varied [x10^-3]
MODAL_196
HT_5
TS.003
LABD4
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Displacement
at LVDT#4
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
-2.4
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS
Analysis Method Varied [x10^-3]
MODAL_511
HT_5
TS.003
LABD3
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Displacement
at LVDT#3
.8
.4
.0
-.4
-.8
.90
.92
.94
.96
.98
1.00
STEP TIME
ABAQUS
Analysis Method Varied [x10^-3]
MODAL_519
HT_5
TS.003
LABD2
Linear Elastic
Material Properties
STANDARD Analyses
Uncracked Model
Acceleration
at LVDT#2
.6
.4
.2
.0
-.2
.90
.92
.94
.96
.98
1.00
STEP TIME

Figure 14

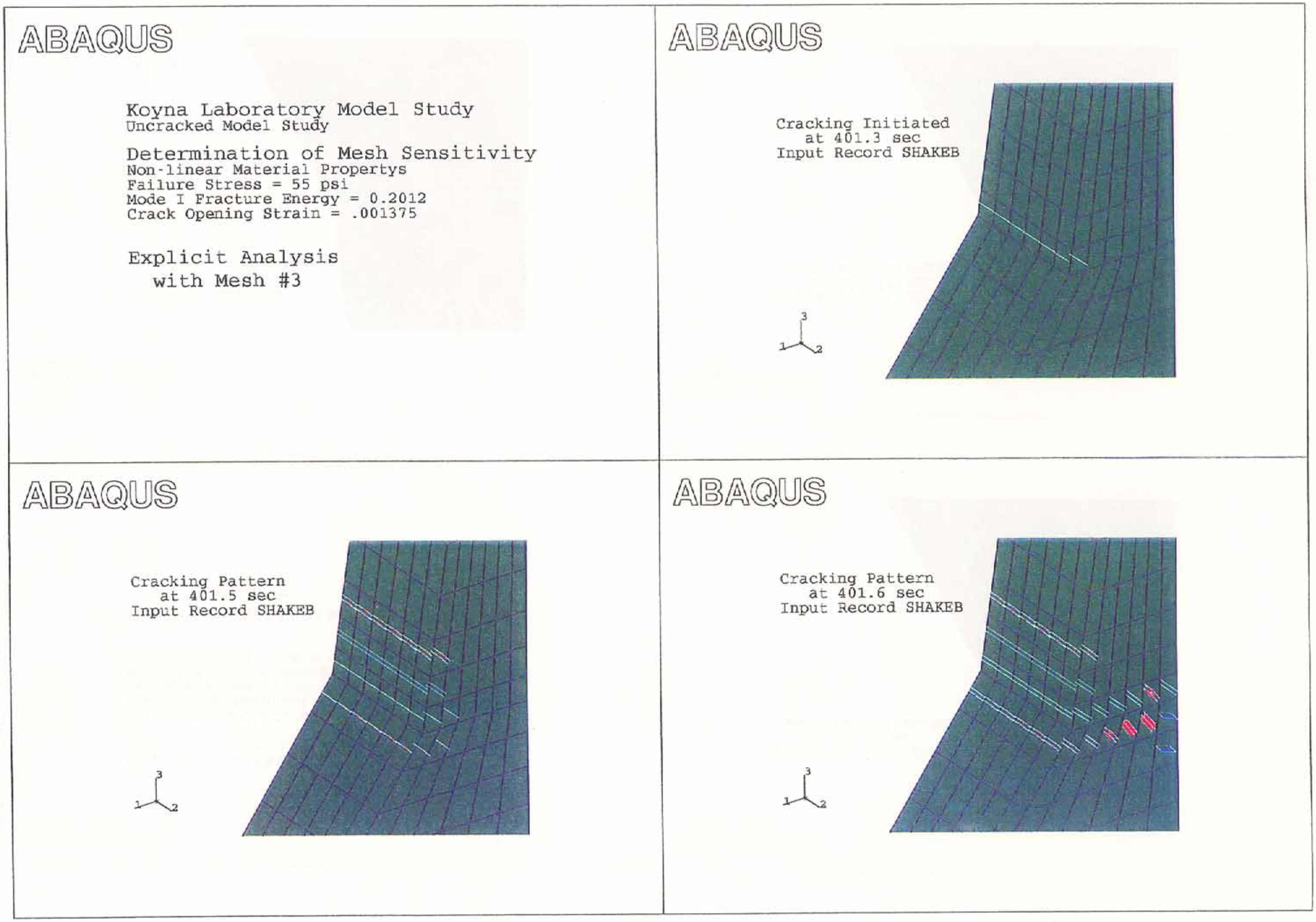

ABAQUS
Koyna Laboratory Model Study
Uncracked Model Study
Determination of Mesh Sensitivity
Non-linear Material Propertys
Failure Stress = 55 psi
Mode I Fracture Energy = 0.2012
Crack Opening Strain = .001375
Explicit Analysis
with Mesh #3
ABAQUS
Cracking Initiated
at 401.3 sec
Input Record SHAKEB
ABAQUS
Cracking Pattern
at 401.5 sec
Input Record SHAKEB
ABAQUS
Cracking Pattern
at 401.6 sec
Input Record SHAKEB

Figure k1

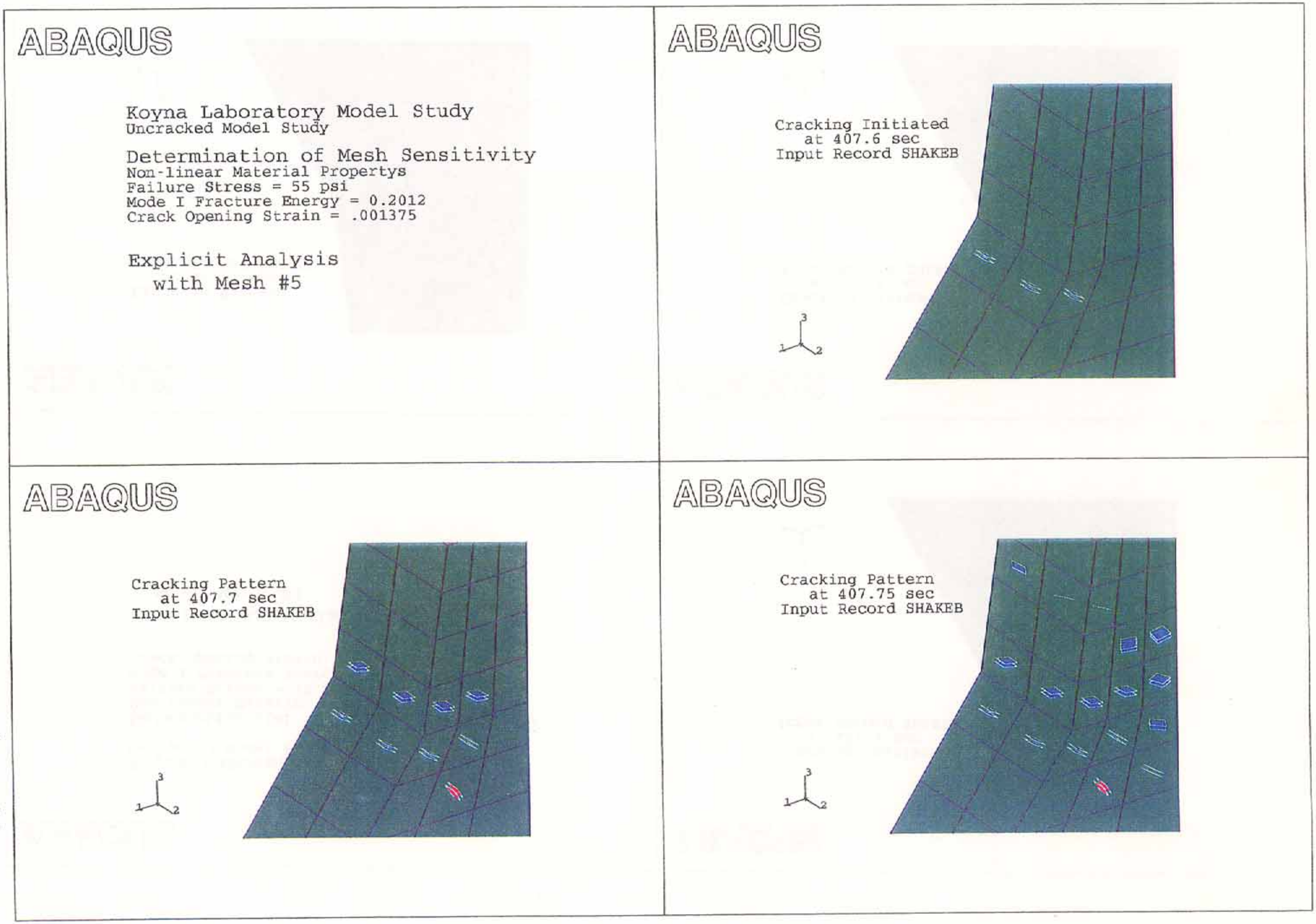

ABAQUS
Koyna Laboratory Model Study
Uncracked Model Study
Determination of Mesh Sensitivity
Non-linear Material Propertys
Failure Stress = 55 psi
Mode I Fracture Energy = 0.2012
Crack Opening Strain = .001375
Explicit Analysis
with Mesh #5
ABAQUS
Cracking Initiated
at 407.6 sec
Input Record SHAKEB
ABAQUS
Cracking Pattern
at 407.7 sec
Input Record SHAKEB
ABAQUS
Cracking Pattern
at 407.75 sec
Input Record SHAKEB

Figure k2

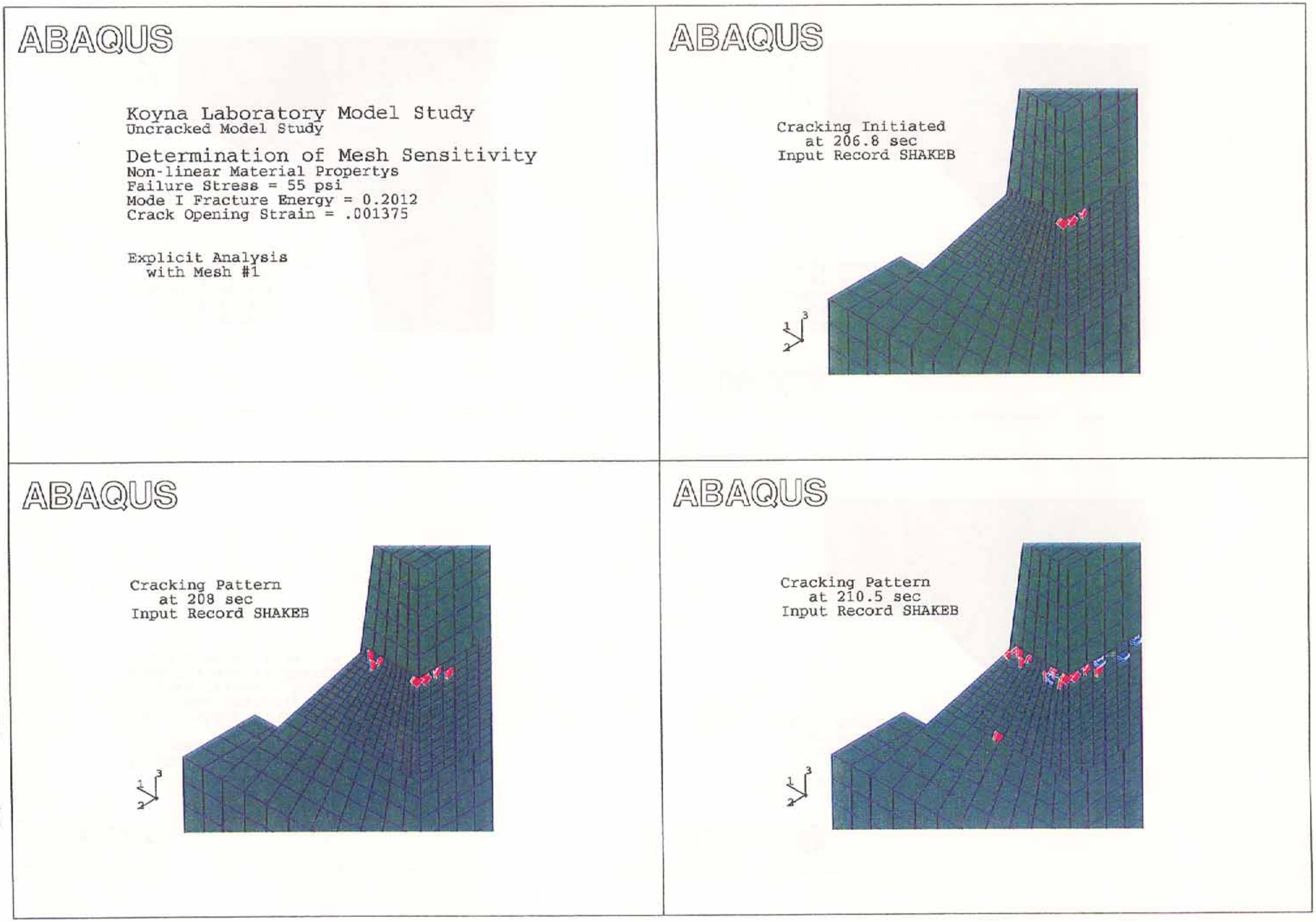

ABAQUS
Koyna Laboratory Model Study
Uncracked Model Study
Determination of Mesh Sensitivity
Non-linear Material Propertys
Failure Stress = 55 psi
Mode I Fracture Energy = 0.2012
Crack Opening Strain = .001375
Explicit Analysis
with Mesh #1
ABAQUS
Cracking Initiated
at 206.8 sec
Input Record SHAKEB
ABAQUS
Cracking Pattern
at 208 sec
Input Record SHAKEB
ABAQUS
Cracking Pattern
at 210.5 sec
Input Record SHAKEB

Figure k3

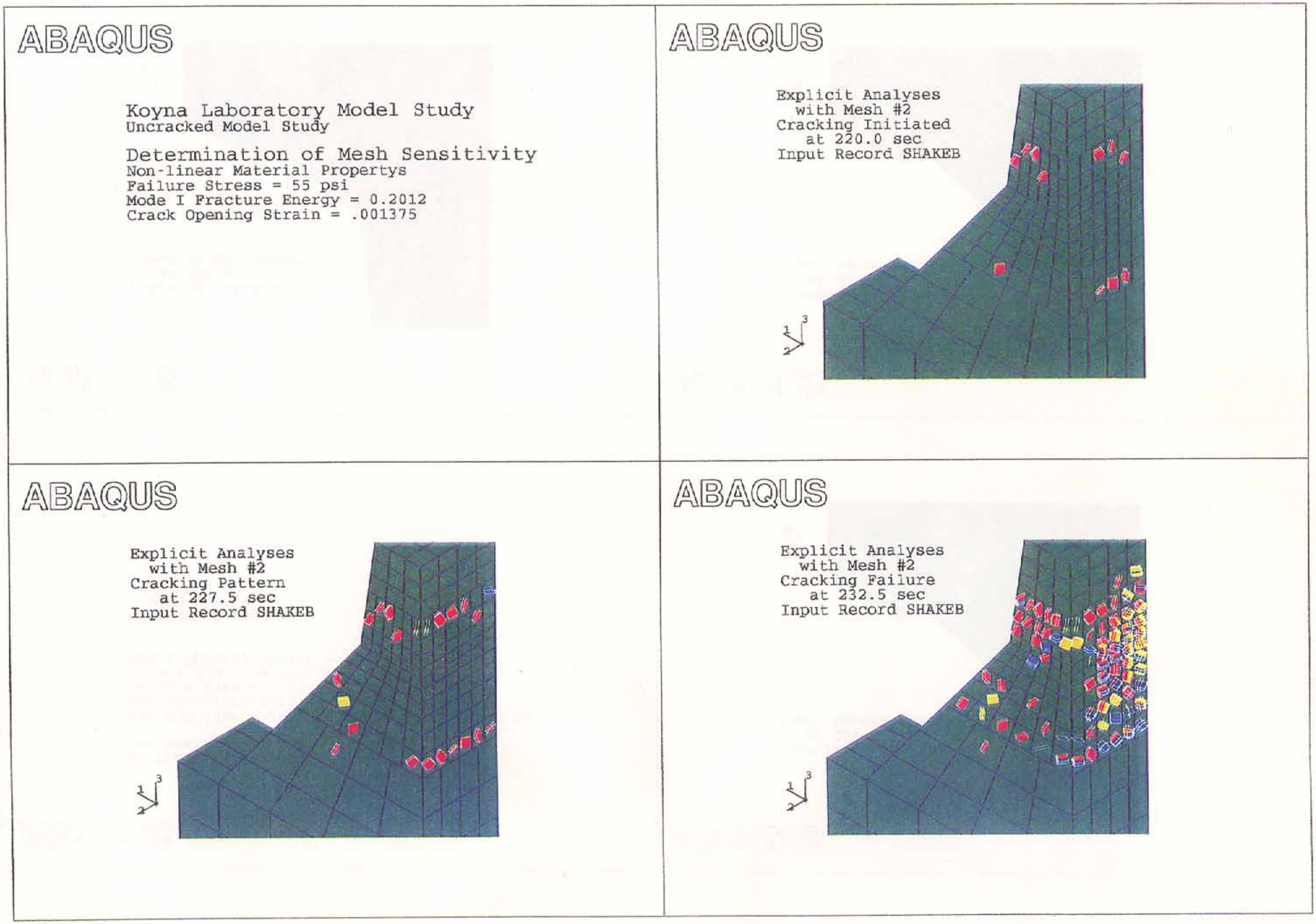

ABAQUS
Koyna Laboratory Model Study
Uncracked Model Study
Determination of Mesh Sensitivity
Non-linear Material Propertys
Failure Stress = 55 psi
Mode I Fracture Energy = 0.2012
Crack Opening Strain = .001375
ABAQUS
Explicit Analyses with Mesh #2
Cracking Initiated at 220.0 sec
Input Record SHAKEB
ABAQUS
Explicit Analyses with Mesh #2
Cracking Pattern at 227.5 sec
Input Record SHAKEB
ABAQUS
Explicit Analyses with Mesh #2
Cracking Failure at 232.5 sec
Input Record SHAKEB

Figure k4